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DESIGN, PERFORMANCE, AND EVALUATION OF SWITCHGEAR FOR SPACE NUCLEAR ELECTRICAL SYSTEMS

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16. Abstract

An ac circuit breaker with a vacuum interrupter for large space power systems has been built and tested in a high-vacuum (10^{-6} torr range) and 1000° F (538° C) temperature environment. The ac breaker, rated 1000 volts, 600 amperes, 1000 hertz, met interrupting and load-switching requirements. The breaker was endurance tested at full rated current for 2700 hours.

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SUMMARY

A single-phase alternating-current switchgear unit, for use in large space power systems, was designed, modified and tested. This device, with the contacts in a vacuum capsule, was based on earlier experimental investigations.

The switchgear unit was developed for operation in a 1000° F (538° C) high vacuum (10^{-6} torr range) environment. The mechanism was equipped with high temperature coils for remote electrical operation.

The switchgear was designed for 1000 volts, 1000 hertz, 1800 amperes (interrupting), and 600 amperes (continuous). The switchgear, together with a separate set of contacts, was endurance tested for 2700 hours. The contacts were subjected to the same current as the functioning device.

The switchgear demonstrated ability to interrupt fault currents of 2400 amperes in 7 to 10 milliseconds. Endurance testing established that the breaker had the ability to close against 3000 amperes (low voltage) inrush current. The molybdenum contacts in both the breaker vacuum capsule and separate capsule exhibited a tendency to weld when closing on high currents (2400 amperes) at the maximum temperature of 1000° F.

The outgassing of materials at 1000° F (538° C) within the vacuum capsule of the interrupter was continuous and appreciable. The vacuum effect on the vacuum capsule moving contact support indicated the need to counterbalance. This would allow the mechanism to operate in the normal sea level environment.

INTRODUCTION

The validity of using a vacuum interrupter unit in large space power system switching devices was investigated in an earlier basic development effort (ref. 1). The early activity established material and design parameters for the design, fabrication and testing of a dc contactor and an ac circuit breaker or switchgear unit. The encouraging results from the mechanical and electrical testing in high vacuum and at high temperatures lead to the present effort.

This activity involved the design modification, fabrication and full-scale interruption testing of an alternating current circuit breaker, a direct current contactor, two contact fixtures and a sealed capsule. This report presents the design and testing results associated with the ac unit having the following design goal: 1000 volts, 1000 hertz, 1800 amperes (interrupting) and 600 amperes (continuous).

All testing was performed in a high vacuum (10^{-6} torr, or lower) and a 1000° F (538° C) temperature environment. The ac breaker was subjected to full interruption, load switching and endurance tests.

One continuously closed contact fixture with full current passing through it was utilized for observations of contact welding phenomenon.

In addition, a second contact capsule was sealed and subjected to the test environmental conditions in order to monitor material outgassing problems.

Final analyses of the molybdenum contacts used in the ac breaker, records of the switching and interruption tests, and the sealed capsule pressure provide design guidance for high power switching devices needed in large space power systems.

DESIGN MODIFICATIONS

Based on the work reported in reference 1, improvements in the design of the circuit breaker were undertaken. These modifications were (1) springs, (2) wipe spring assembly, (3) terminals, and (4) breaker radiators. As the work and preliminary testing progressed, it became evident that further improvements in the design were desirable. These improvements involved (1) the mechanism, (2) interrupter capsules, (3) the current shunts, and (4) test circuit. Figure 1 is a cross section of the breaker showing the areas in which design changes were made.

Springs

The earlier mechanism opening springs and the contact wipe springs, made of spring temper Inconel X 750, lost strength during the 1000-hour endurance test (ref. 1). The reduced load deflection characteristic was the result of a permanent change (reduction) in free length.

An investigation was initiated into the problems of springs for high temperature and long life. The work and results are covered in detail in reference 2. This led to the selection of Inconel 718 as the preferred material. Springs made of the same material and with the same processing as for the tests in reference 2 were obtained for the new switchgear. All were checked prior to the buildup, and again after all the tests were complete. The results will be discussed in a later section.

Two springs were used to provide pressure on the closed contacts of the ac breaker, with a maximum of 50 pounds required. The two springs used in parallel were to keep the stress in the spring wire to the desired low limits. The opening spring and the wipe spring are shown in figure 2.

Wipe Spring Assembly

The redesigned breaker contact wipe spring assembly is shown in figure 3. This assembly consists of a high purity ceramic shell, the two (inner and outer) compression springs, and a nut holding a split cup that surrounds the center part of the ceramic. It is assembled with the springs preloaded to a 40-pound value. Thus when the breaker contacts touch, force on them builds up at once, and the 1/8-inch additional mechanism movement raises the compression (spring) force to 50 pounds.

Terminals

The original circuit breaker for interruption tests had copper terminals attached to the capsule conducting parts, using a tapered pipe thread. These provided a good secure electrical joint but were difficult to assemble tightly in the correct position. After a period at high temperature in vacuum, it was very difficult to remove the terminals for disassembly of the samples.

To improve this assembly, new terminals were designed which could be attached to the copper conductor parts by means of high strength A-286 bolts and nuts. The difference in expansion characteristics of the copper and stainless steel were expected to cause some loosening of the joint if it were cycled from high to low temperature. This would be satisfactory if the high temperature were maintained, as expected, during the test.

Breaker Radiators

Heat is removed from the breaker contacts, by conduction through the copper flanges on the vacuum capsule assembly, to copper radiators with an iron titanate coating for high heat radiation. The inside of the breaker interrupter shell is also coated with iron titanate to receive heat from the capsule radiators. The heat is then conducted to the heat sink mounting plate.

The previous series of tests (ref. 1) showed that the top contact moving radiator tended to move from its normal shrink fitted position. Also, the bottom flange tended to move out of the lower radiator support and for the support to distort. These problems were caused by the high impact forces during a closing operation.

Both problems with the radiator security were solved by pinning the radiators in place on the flanges, then adding a stainless steel backup ring under the lower flange. The breaker capsule, with radiators pinned and the ring in place, is shown in figure 4.

Mechanism

The breaker was to be operated by a mechanism that would permit rapid operation in a high temperature vacuum environment. Based on the data obtained from the initial tests (ref. 1), a study was made and a new design chosen based upon a flux-shift latch principle. The flux-shift latch would require a permanent magnet that was suitable for use at 1000° F (538° C) for long periods of time without a decrease in holding force.

Flux-Shift Latch. A suitable design of magnetic latch was developed and incorporated into the original basic mechanism. A cross section of the improved design is shown in figure 5. Three flux-shift latches are arranged around the mechanism's central core (with its closing coil and armature) between the three opening springs. The latch armatures are attached by flexible pins to a three-pronged plate mounted to the top moving assembly. The moving parts are kept in position (and the closing armature centered in the core) by stainless steel flexible diaphragms at the top and bottom of the mechanism. Refer to figure 1 for a cross section view of the overall device.

A high strength magnet is mounted between the soft iron side pieces just above the mounting plate. It provides a flux which follows a path across the pole pieces and through the armature when it is in the closed position. A 0.002-inch or 0.003-inch tantalum foil shim is held in place to provide a small gap in the armature. The trip coil is mounted on a slotted iron core between the side pieces, with a 0.020-inch gap in the magnetic circuit.

In operation, when the armature is closed, the flux path is from the magnet, through the side pieces, across the short gaps and through the armature, providing a strong armature holding force. When the trip coil is energized, the resulting magnetomotive force overcomes the large gap reluctance. The flux then follows the new and shorter path through the annulus of the trip coil. This decreases the armature holding flux by 95 percent or more, so the armature is released from the closed position. Release time is as short as 3 milliseconds. One of the magnetic latches is shown in figure 6.

Magnets. The holding force of the Alnico-8 magnets originally used in the latches was marginal, based upon preliminary bench tests. A review was made of available permanent magnets. Figure 7 is a plot of various parameters which pertain to the latch and magnet. Curve A shows the published value of the Alnico-8 magnet material. Curve B is the demagnetization curve for the actual magnet from the latch which showed the lowest pull. Curve C is for Alnico-5 (grain oriented) while Curve D is for Alnico-5-7, a specially cast and processed material with a highly developed directional grain pattern. The straight line, Curve E, is the load line for the specific magnetic structure which is used for the mechanism latch. It is the magnet permanence coefficient and slope is (-B/H).

A comparison of Curves A and B indicates the magnet flux is down about 10 percent from the normal published data. The load line, however, has more slope than was originally expected, but not so much that the relatively low demagnetizing force (H_c) of Alnico-5 would be a problem. Alnico-8 was originally selected because of its high H_c in case the load line was more to the left, and also because available technical information indicated somewhat lower loss of energy at high temperature than Alnico-5. However, in view of the data subsequently available, it was apparent that Alnico-5 would provide more useful force at the operating point. Therefore, the magnets were changed to Alnico-5.

With the higher energy of the Alnico-5 magnet, the flux at the pole tips as well as the armature increased. Therefore, a review was made to check for possible saturation. The results are tabulated below for three important points in the latch structure for the two magnet materials considered.

Data Point	Alnico-8	Alnico-5
In Magnet	58,700 lines 7,410 gauss	80,000 lines 10,000 gauss
At pole tip	24,600 lines 14,950 gauss	33,600 lines 20,400 gauss
In armature	25,400 lines 15,400 gauss	34,600 lines 21,000 gauss

Saturation of the cold rolled steel, according to available data, takes place at about 21,000 gauss. Thus the pole faces are almost at this limit with Alnico-5, but should be satisfactory. The armature, however, would be at the saturation point. The armature was redesigned by increasing the cross section about 25 percent and using ingot iron which has an indicated saturation value of 21,000 gauss. The armature will then attract some of the fringing flux which is also present near the pole tips.

With the change in magnet material and armature design, the latch holding force with a 3-mil gap increased about 30 percent. The new total of 165 pounds for the 3 latches was about 100 percent above the design holding force of 77 pounds. This provided the margin needed for holding during the closing motion.

Solenoid. To protect against rubbing and binding at the high operating temperature of the mechanism, sleeves made from cobalt-25% molybdenum (Co-25Mo) were used on the armature and for the upper core liner. In vacuum, friction tests with sliding velocities up to 2100 feet per minute indicated a sliding friction coefficient of 0.3 for Co-25Mo on itself (ref. 3). Due to different coefficients of expansion of the materials (liner, sleeve and armature), clearances were calculated to prevent overstressing the Co-25Mo at temperature.

The mechanism has a minimum capacity (closing force) of 100 pounds required to compress the wipe spring assembly (50 pounds) and the three trip springs (27 pounds). If a sufficiently uniform radial clearance could not be maintained between the armature and the solenoid core, a magnetic side force of 29.3 pounds would exist (ref. 4). The sliding friction force to overcome the 29.3 pounds is 8.8 pounds which when added to the wipe spring and trip spring forces falls below the total solenoid force of 100 pounds. Sufficient clearance was maintained throughout the core section to prevent any binding. The modified mechanism with new latching parts is shown in figure 8.

Interrupter Unit

Interruption and switching of the electric circuit takes place in the vacuum capsule that is located in the supporting shell. The capsule is shown in the center of the supporting metal shell in the lower part of the breaker (fig. 1).

Ceramic Shell Design. The previous ceramic assembly with metal attachments was apparently the location of occasional flashover as interruption tests were made. A design and literature review (ref. 3) showed that the several metal-to-ceramic interfaces should preferably be shielded to prevent high voltage stress concentrations. In vacuum an electron discharge takes place from the negative terminal in a line-of-sight manner. When the electron stream impinges on a positive metal terminal point, high metal erosion and surface tracking take place. This phenomenon reduces the withstand voltage value of the configuration as much as 75 percent.

Voltage stresses in the new design, ceramic shell assembly (fig. 9) are reduced with the metal junctions protected by the ceramic. Further, no metal actually passes through the ceramic. A high temperature gold-copper (50-50) braze alloy was used to attach the spinnings to the molybdenum-manganese metalized ceramic (99.5 percent alumina) surfaces. Leak checks showed the assemblies used in the test samples to be completely tight.

Vacuum Capsule. The vacuum capsule assembly includes the interrupter capsule, a stainless steel bellows, and copper flanges to which are brazed the molybdenum contacts. Brazed to the contacts are rodar spinnings which are welded to the ceramic shell and bellows. A stainless steel tube projecting from the bottom spinning provides the means for evacuation and seal-off of the capsule (fig. 10). The two test samples had capsules open to the tank vacuum through the open evacuation tube. The sealed unit with an attached 0.5 liter per second ion pump obtained outgassing data. Contacts in the sealed capsule samples were held closed with springs providing a 20-pound force. The capsules were used to determine if any welding or sticking developed during the test program.

The interruption capsule was opened to the vacuum chamber. There were no differential pressure forces present such as would occur in a sealed capsule. Any future requirement, where the capsule has to be evacuated and sealed, will necessitate special procedures to overcome the forces on the capsule due to air pressure on the outside of the evacuated chamber. The springs will have to be changed for test purposes or equivalent opening forces obtained by some other means. This is necessary if the breaker is to be operated on the launch pad.

The sealed capsule sample is shown in figure 11. The ion pump would operate only as long as the surrounding temperature was below 700° F (371° C). To obtain this condition during testing at 1000° F (538° C), a heat shield (10 layers of stainless steel foil with wire separators) was placed over the pump enclosure through which air was circulated from outside the test tank using the bellows hose shown in figure 11.

AC Current Shunt

A detailed study of the ac shunt diaphragm confirmed that fatigue cracking of the copper was taking place rapidly in the

1000^{o} F (538^{o} C) temperature, high vacuum environment. It was desirable that a new design fit into the existing breaker configuration to keep the rework effort to a minimum. The final design shown in figure 12 was built and tested for the final endurance test.

The arch-shaped conductor or shunt is composed of eight strips each measuring 0.50-inch wide and 0.006-inch thick. The complete assembly for the breaker utilized eight of these shunts (ref. 5). A stress analysis of the arch-shaped conductors confirmed the possibility of using Berylco-10 alloy or Cube-alloy. Berylco-10 alloy appeared feasible from a stress standpoint but not from the electrical conductivity requirement. With a current flow of 600 amperes through the assembly, the current density is 3120 amperes per square inch. Since Cube-alloy was satisfactory from both the stress and electrical conductivity requirements, it was used to fabricate the new current shunt assembly for the ac breaker.

Auxiliary Contacts

Improvements incorporated into the test circuit included the addition of auxiliary contacts on the breaker. These were incorporated to indicate position of the breaker mechanism, essential for proper and full recording of the operation.

The stationary contacts were mounted on high purity alumina to provide two insulated connection (contact) points. The moving contacts were attached to the mechanism moving top plate. As shown in figure 13, they were arranged to be adjusted by loosening the holding screws.

A small battery and resistor were connected between ground and each insulated contact and in series with a galvanometer on the visicorder. When the contacts closed the galvanometer was deflected. The adjustment was such that the one contact closed at the full-open position of the mechanism, and the other at the full-closed position.

Final room temperature checkouts of the assembled breaker with the final modifications showed good performance with prompt closing and holding of the latches. Tripping was also prompt and at the expected speed. The unit (fig. 14) was remounted to the heat sink and leads attached for final interruption, switching, and endurance testing.

TEST APPARATUS

For the endurance testing the load current was 600 amperes, 60 Hz. The current was obtained from a low voltage, high current, reactor controlled transformer.

The power for the interruption tests was obtained from a ringing circuit to provide the desired 1000 Hz. A bank of 600 volt, high Q capacitors, connected in a series-parallel configuration, was used with a high Q inductance coil. The capacitors were partially discharged during the interruption test. Accurate timing and fast moving contacts were required for minimum capacitor discharge and therefore maximum recovery voltage.

Test Specimens

The ac breaker, complete with mechanism and interrupter (fig. 1) was energized for close-open operations and interruption tests. Object of the test was to subject the breaker to opening operations to check short circuit interrupting ability. Full-load switching (close-open) tests were to be made at various time intervals and final interruption tests after 2500 hours. An event recorder with a time scale was used to measure the following data: voltage across contacts, current through contacts, close-coil current, trip-coil current, and auxiliary contacts position.

The ac contact fixture, consisting only of the interrupter unit with a clamp on top (fig. 15), was energized with the same power as the breaker during the test programs. The contacts in the contact fixture remained closed throughout the program. By flowing current through the fixture contacts, a study of material erosion, surface pitting and contact welding phenomenon could be made.

The sealed capsule (fig. 11) with nonenergized contacts had its own vacuum pump. The contacts were held closed with springs to see if any welding or sticking would develop in the environment over a long-time period. The sealed unit was to provide outgassing data during long time in a high vacuum and 1000° F (538° C) temperature.

Controls

The test sample close and open (trip) coils were supplied from suitably sized charged capacitor banks. A schematic diagram of the control circuitry is shown in figure 16. Also shown are the test operators sequence for making the tests with an indication of what takes place during the sequencing. Electronic timing relays are used to control the close operation of the test samples and coordinate it with the power supply availability. They also control the length of the time the visicorder operates. Thus with the timers adjusted, the interruption test will be automatically performed and the results recorded after the operator initiates the sequence.

Test Power Supply

Modifications made to the ac test power supply included the addition of capacitors to reach the higher test currents, and the development of a new inductance coil. A study of the test interruption requirements and the best combination of circuit components is included in Appendix A.

The breaker operating speed is limited by the moving mass and strength of the mechanism operating springs. A series of bench tests showed that the minimum time the contacts could be expected to be closed (during close-open operation) was 18 milliseconds. The results of the study in Appendix A are summarized below:

			Initial		Final		Time to
Case #	L (Mll)	C (Mrd)	Amps	Volts	Amps	Volts	Final
IA	88.5	287	2160	1200	1800	1000	5.44 ms
IB	88.5	287	2160	1200	1200	667	17.3 ms
II	133.0	191	2160	1800	1200	1000	19.6 ms
III	58.0	440	3600	1300	1800	650	17.9 ms

Case IA has the specified final values, but the short time for the power to decay to them from the preferred initial values makes the use of this combination unrealistic in view of the 18 milliseconds that the contacts will be closed. Case IB shows the lower voltage and current that results for a time of almost 18 milliseconds. Other possible circuit parameters and initial (capacitor charge) conditions are shown by Cases II and III. Case II with more L and lower C and a higher charging voltage still does not provide enough current at interruption. Case III with lower L and higher C, will give full current but lower voltage at the interruption point.

The arrangement with the Case III conditions was selected as being the most realistic for proving the breaker rating without too greatly exceeding the breaker contact closing capacity. The somewhat low voltage at interruption does not appreciably reduce the duty on the breaker because it is well known that the vacuum interrupter is more current than voltage sensitive. By increasing the voltage applied to the capacitors and the energy of the ringing circuit, opening tests would be at rated voltage and slightly above current rating. This test would explore performance above design point.

Installation of a fast operating air switch for circuit closing, plus modifications of the control circuits, permitted opening tests with the breaker trip coil power synchronized with the closing of the air switch. All ac capacitors were housed in one cabinet with very short leads. All nearby magnetic material was removed to reduce hysteresis and eddy current losses.

Analysis of the layer wound coil (with thin flat copper strip) used in the last series of tests led to the conclusion that losses were higher than expected or useable. Therefore, a study of coil design led to the development of a single layer coil using Litz cable; with the coil length approximately equal to the diameter for best efficiency.

A coil for the Case III condition noted above, providing a 1000 Hz test frequency, used a conductor consisting of 3-400 MCM (copper section) Litz cables, twisted as they were assembled in parallel to provide a total cross section of 1200 MCM. Each cable consisted of 7 groups of 7 cables, each with 82 insulated #30 wire, on a 0.44-inch jute center. The cable bundle was insulated with a neoprene boot (zipper tubing) and placed on a wooden reel to provide a coil with a mean diameter of 27 inches and length (cable center line) of 26 inches. Heavy terminals were soldered to the ends of the cables, taking care to be sure the individual wire insulation was fully removed before attaching the terminals.

The test and recording equipment connected up and ready for interruption testing is shown in figure 17. Note the inductance coil with one terminal attached to the ac selector switch and the other (hidden) attached to the cabinets with the capacitors in the center back of the picture. The test samples are inside the vacuum tank. The feed-throughs at the bottom of the tank are for lamp (oven) power, control, and testing power, and all thermocouples. Testing control and recording equipment is in the cabinets at the left of the picture.

RESULTS AND DISCUSSION

Preliminary Testing

Timing tests showed that the time constant (time for the current to decrease to 37 percent of original value) had changed from 16 to 22 milliseconds after the circuit arrangements modifications had been incorporated into the system. The breaker was operated and checked out at room temperature with the close and trip coil power supplies (capacitor discharge) set for optimum performance. Visicorder records of typical operations showed the following:

(1) With breaker closed and the mechanism latched, breaker starts moving in 2 milliseconds after trip coil is energized, and is fully open in 17 milliseconds.

(2) With breaker open and mechanism reset and trip coil energized (mechanism will not latch in closed position) breaker starts moving in 9 milliseconds, main contacts touch 2.5 milliseconds later, mechanism is fully closed in 10 milliseconds, and contacts part (circuit interrupted) in 19.5 milliseconds after they first touched.

These data indicate that (at room temperature) the time the power circuit would be closed is less than 20 milliseconds so the test circuit time constant of 22 milliseconds would be acceptable.

Interruption Tests

The breaker was subjected to three full power close-open operations at the beginning and termination of the endurance test. Additional tests were also performed at reduced power checking short circuit interrupting ability using a source to provide 1800 amperes rms (initial) and 650 volts rms (minimum) at interruption while stablilized at 1000° F (538° C) in a vacuum chamber. An event recorder (visicorder) with a time scale measured the following data: voltage across the contacts, current through the contacts, close coil current, trip coil current, and auxiliary contacts position.

Data obtained from both series of interruption testing is given in table I. It shows overall performance of the test circuit and the effect of changes in the capacitor bank charging voltage on available current and voltage at the time of interruption. The frequency was just under the desired 1000 Hz with consistent operating times. By charging the capacitor bank with a low value of voltage and increasing same, the circuit capability was verified for the test specifications at interruption. It is to be noted that the breaker successfully interrupted the current at a value 50 percent higher than the specifications called for.

The breaker functioned properly and met the required specifications of the program, interruption and close-open switching operations. Contact sticking or spot welding occasionally was encountered, requiring a temporary decrease in temperature within the chamber. This increased the opening spring force slightly (and probably affected the weld) which was sufficient to permit the contacts to open.

Figure 18 is a typical visicorder record of an open only interruption test. The breaker is in a closed position and carries a 600 ampere normal load at the start of the interruption test. The 600 ampere load is cut off by the air switch at the instant the fault current from the capacitor bank is tripped. Trace "A" shows the capacitor bank charged to 1250 volts, while trace "B" indicates the fault current discharged from the capacitor bank (with an initial peak of 3600 amperes) through the breaker lasting for 10.4 milliseconds. The trace "D" is the mechanism trip coil current. The auxiliary contacts, trace "C", indicate complete opening of the breaker contacts in 31 milliseconds. No movement is shown on the closing coil, trace "E", as the breaker had been closed initially on the 600 ampere load.

Endurance and Load Switching Tests

The breaker and contact fixture connected to heat sinks were subjected to their normal current ratings while in vacuum and a 1000° F (538° C) environment for a total of 2700 hours. Furthermore, the breaker was subjected to at least three close-open tests, switching the normal current of 600 amperes at the end of these periods of endurance test time: 5, 15, 30, 100, 200 hours and then each succeeding 200 hours with a final series at the end of the endurance test. Prior to starting the tests, then before and after each series of switching tests, and at the end of the endurance test, the contact resistance (by the voltage drop method) was determined.

The values obtained from the series of measurements, during the endurance test are shown in table II. It is to be noted that the final resistance value is below the initial value and never increased. The contacts, therefore, did not deteriorate but were actually conditioned during operation.

Results of typical load switching tests conducted after the 2700 hour endurance run are shown in table III. A total of 32 load switching operations were initiated with several conducted at each current level. The auxiliary contacts were closed ahead of the main contacts, two to three milliseconds, because they (auxiliary contacts) were positioned to have a slight wipe action to insure good contact. The consistency of the breaker operation can be noted from the closing and opening times.

The planned combination endurance-switching test series was successfully completed. Temperature rises in the ac breaker and contact fixture while carrying 600 amperes was a maximum (at upper terminals) of 60 to 70° F (15 to 21° C), with the heat sink temperatures held at 1000° F (538° C).

Some occasional sticking of the breaker contacts occurred during some of the switching tests, due apparently to the high inrush of the low voltage ac supply circuit. This circuit included a saturable reactor control for the high-current transformer output. This control did not limit the inrush which occurred when closing the breaker. It required nearly one second for the inrush current (which was as high as 3000 amperes) to decay and be controlled to the required 600 amperes. However, when the control was preset to the desired value and manually operated, the inrush current was limited to approximately 600 amperes. This sequence of operation was used for the majority of the switching tests.

Figure 19 is a visicorder record of a typical close-open switching operation. To insure that the breaker latched properly, the trip part of the cycle was delayed about half a second. The voltage, trace "A", is the 60 cycle, 10 to 15 volts load source from a large low voltage transformer. When the closing coil is activated, trace "E", the breaker closes in on the load, and current flows, trace "B". The auxiliary contacts, trace "C", show the mechanism being closed in 23.5 milliseconds and remaining closed for 0.48 seconds. The main contact current, trace "B", shows the current flowing for 24.8 milliseconds after contact closing is initiated. After being closed for the 0.48 seconds and carrying the final steady state 600 amperes current, the trip coil is activated with the main contacts opening in 8.0 milliseconds. The auxiliary contacts, trace "C", show full contact opening in 27.6 milliseconds after trip current is applied.

POST-TEST ANALYSIS

Upon completion of the test program, the breaker and capsules were removed from the vacuum tank and dismantled to visually and metallurgically analyze their condition.

Contact Fixture

The dismantled contact fixture is shown in figure 20. The stainless steel clamping bar and related parts had a dark blue coating which was hard and very thick. The alumina insulation pieces are all darkened with a grayish coating while the copper shell showed some oxide discoloration.

In dismantling the fixture it was found that the clamping disc between the wipe spring assembly and the copper diaphragm were diffusion welded together and to the top flange of the capsule. This required that the diaphragm flexible leaves be cut for removal. The shunt leaves showed no sign of stress cracking; however, they did not move during the more than 2700 hours in vacuum at 1000^{o} F (538^{o} C). The copper terminals were found to be slightly loose. This was apparently due to the differential thermal expansion of the A286 clamping bolt which deformed the copper terminals. On cooling to room temperature, the copper remained deformed and therefore the bolt loosened. The radiators were removed with difficulty because they had diffusion welded to the capsule flanges during the test time. Then the capsule was cut apart. The inside of the capsule ceramic was clean, as were the rodar end spinnings. However, they had a grayish dull surface coating as indicated in figure 21.

Around the stainless steel tubulation entrance was a darker smear; this apparently is an oxide from the stainless steel caused by the high temperature and possibly a lower vacuum than the measured 10^{-6} torr or better, due to the contact fixture being at the top of the oven and furthest from the ion pump and ion gauge.

The contact surfaces in the breaker fixture showed definite evidence of surface pitting, as can be seen in figures 22a (top contact) and 22b (bottom contact). This pitting is undoubtedly caused by the high short circuit currents (3000-4000 amperes) during interruption and switching tests. However, this surface change did not result in any welding or sticking, for the contacts came apart freely when the wipe spring pressure was removed. The surfaces after the more than 2700 hours of testing can be compared with the surfaces before the capsules were assembled, as shown in figures 23a (top) and 23b (corresponding to the a (top) and b contact surfaces in figure 22).

Sealed Capsule

The sealed capsule subjected to the high temperature of the test environment had been in a condition of vacuum (less than 10^{-6} torr) for a period of nearly two years. During this time no leaks developed.

The inside of the capsule (ceramic and metal parts) was, if anything, cleaner and brighter than when it was assembled. A closeup view of the contact surfaces at the end of the test is shown in figures 24a (top contact) and 24b (lower contact). The surfaces before assembly are shown in figures 25a (top contact) and 25b (lower contact). The small marks scattered on the contact surfaces after the two-year period are superficial. They were apparently caused by physical handling of the capsule (contacts jarring each other) prior to final clamping and evacuation.

During the test period, the ion pump maintained a vacuum and was used to indicate approximate pressure in the capsule by using pump current as a pressure indicator. At room temperature conditions the pressure was in the 10^{-8} torr range. However, when the capsule was heated to 1000° F (538° C) the pump was only able to maintain a pressure in the 10^{-6} torr range. This indicated appreciable and continuing outgassing from the materials in the capsule, even though they had been carefully processed and baked out above the operating temperature during assembly.

Breaker

The breaker was dismantled and the parts are shown in figure 26. The condition of the various parts was similar to that observed in the contact fixture. The alumina insulating rings were darkened with a grayish coating, especially at the holes in the shell where the terminals were attached. The terminals and the interrupter shell were slightly oxidized. One terminal was slightly loose. This was undoubtedly caused by deformation at high temperature of the copper under the A286 high strength bolt.

The springs were slightly blued, but tests indicated little change in characteristics. Table IV shows relaxation of the springs during test. The relaxation is well within the 5 percent limit change set as a requirement (ref. 2). Table V gives pretest and post-test data for mechanical loading of the springs. A slight increase in strength is apparent, which might be a form of cyclically strain-hardening (ref. 6).

The breaker capsule was mounted in a fixture to remove the radiators and then cut apart. The top and bottom contacts, and the ceramic shell with the center shield are shown in figure 27. The lower radiator is still attached to the lower flange in this picture. Note especially that the shield in the ceramic cylinder was spattered with metal particles from the molybdenum contacts. The particles were ejected outward during closing on high inrush currents or during the high power interruptions. Metal spatter is also clearly visible at the base of the top (moving) contact marked #1 in figure 27 and was slightly present inside the bottom shield.

A closeup view of the contact surfaces is given in figures 28a (top contact) and 28b (bottom contact). These same contact surfaces, before assembly into the breaker capsule, are shown in figures 29a and 29b. They had been prepared by turning and smoothing with a #600 grit abrasive. It can be noted that the erosion of the surfaces due to the switching operations is extensive. It was also observed that apparently the two contact surfaces touched slightly off center. In closing at the high temperatures, the molybdenum was melted momentarily at the points of contact and sprayed along the sides of the top contact.

The bottom contact was sectioned, polished and etched. Microphotographs were taken of the contact surfaces as well as the brazed areas where the molybdenum contact was attached to the Amzirc flange. Evaluation of the microstructure beneath the eroded surface areas confirmed that melting had occurred. Figures 30a and 30b show one of the many areas that indicate a recast structure. It is apparent that during the switching tests some of the areas have been heated, worked, and recrystallized. They show a mixture of fine columnar and equiaxed grains. Just below the recast area, between 5 and 10 mils from the surface, the heat from arcing has caused the material to recrystallize. This indicates that the heat from arcing dissipated rapidly near the surface.

Cracks can also be seen in the recast and recrystallized areas that follow grain boundaries and cleavage planes. The brittle recast and brittle recrystallized grains cleaved to relieve the stresses caused by the mechanical forces generated during the switching operations at the operating temperature of 1000° F (538° C). The grain boundary cracks are probably derived from a thermal origin caused by the higher temperatures of arcing. The voids seen are probably the result of cracks that completely encompassed grain(s). During polishing these areas were pulled out.

Close inspection of the brazed molybdenum contact assembly indicates that the molybdenum contact moved back toward the Amzirc flange on one side. Measurements indicated a 33 mil difference in elevation from one side to the other of the contact. The microstructural evaluation in the braze area indicated a lack of braze on the side that was back extruded, as can be seen in figures 30c and 30d. Apparently, the combination of the dynamic force on the contacts during closing, the force to maintain the closed position (50 pounds), plus the lack of braze on one side, caused the contact to tilt and deform the end flange.

The evaluation indicates that arcing undoubtedly caused the damage observed on the contacts. Arcing not only eroded the contact surfaces, it also increased the unit stresses acting on the contact surfaces. These high unit stresses along with the increased local heat from higher current densities caused contact sticking.

The brazing reliability can be improved by using a more rigid brazing fixture, and by nickel plating the molybdenum contact brazing surfaces to improve braze metal adherence.

CONCLUDING REMARKS

This program, established to rebuild and extensively test an ac breaker and contact fixtures, has been completed and basic objectives accomplished. An endurance test was terminated after 2700 hours and the vacuum capsule in the breaker satisfactorily interrupted (or switched) the maximum ratings. During the test, switch closures occurred with an inrush current 5 to 6 times the normal rating which contributed to erosion and occasional contact sticking. The indication suggests that possibly another material might be better for the contacts than molybdenum.

A more basic problem involves the building and application of a sealed-off capsule. It needs to be improved so the outgas at the high temperature specified (1000° F, 538° C) is minimal, or a high temperature getter becomes available which will absorb the gas coming from the inside surfaces over a long period of time. Terminals, and their attachment to the current carrying parts, could be further improved through use of a stronger material such as Cube-alloy that does not weaken at high temperatures. The fastening hardware also needs further attention to provide a ready attachment that can be easily removed.

The mechanism proved to be very suitable after the various refinements were made. The magnetic latch design should be highly useful for flight-type hardware of various switching devices. This latch is simple, suitable for high temperature environment, has no sliding surfaces to gall, and will release with high speed when the flux shift coil is energized. Springs used for the mechanism and contact pressure, made of Inconel 718 and designed in accordance with reference 2, operated with complete satisfaction in the 1000° F (538° C) environment.

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2. Powell, A H.: Compression Springs for Long Time Operations in Vacuum at 1000^{o} F. NASA Topical Report, General Electric Company, November 1969. (NASA CR-107740, 1970.)

3. Kofoid, J J.: "Phenomenon at Metal-Dialectric Junctions of High Voltage Insulators in Vacuum and Magnetic Field,", Vol. 70, No. 3, Power Apparatus and Systems, AIEE Transactions, December 1960, pp. 991-999.

4. Buckley, D. L., and Johnson, R. L.: Marked Influence of Crystal Structure on the Friction and Wear Characteristics of Cobalt and Cobalt Base Alloys in Vacuum. NASA TN D-2525, 1964.

5. Mueller, L. A.; Snider, W. E.: Flexible Electrical Conductors for High-Temperature Switchgear. NASA TM X-1986, 1970.

6. Manson, S. S.: Thermal Stress and Low-Cycle Fatigue, Chapter 4, McGraw Hill Book Company, 1966.

TABLE I

AC BREAKER - INTERRUPTION TEST DATA - 950 Hz POWER

Test No. Before Endurance Test	Capacitor Charge-Volts	RMS Voltage at Interruption	Inrush Current-rms	RMS Current at Interruption	Time Power Flowed-Millisec.
1	750	310	840	390	10
2	750	265	830	375	11
3	1000	400	1600	1300	10
4	1500	800	2100	1620	12
5	1500	No Trip Current	3000	No Interrup.	--
6	1500	700	2800	1800	14
After Endurance Test					
1	1000	520	1960	1409	9.2
2	1000	530	1960	1439	8.8
3	1000	500	1960	1372	10.0
4	1000	520	1960	1439	9.0
5	1000	No Trip	1960	Calibration Check - Frequency 956 Hz	
6	1250	462	2540	1270	20.0
7	1250	802	2540	2240	5.6
8	1250	693	2540	1910	10.0
9	1500	960	3040	2650	5.0
10	750	No Trip	1550	Calibration Check - Frequency 948 Hz, Time Constant 23 ms	

TABLE II

AC BREAKER - CONTACT RESISTANCE DATA DURING ENDURANCE TEST

Hours on Test **	Voltage Drop (600 A, AC)*
Initial	0.393
21	0.323
95	0.350
190	0.340
430	0.358
620	0.340
808	0.358
1004	0.355
1195	0.350
1360	0.350
1600	0.350
1791	0.345
1984	0.360
2236	0.380
2426	0.370
2693	0.380

* - Voltage drop and calculated resistance includes one power lead.

** - Measurements made after the series of switching tests at the elapsed times noted.

TABLE III

TYPICAL CLOSE/OPEN TESTS CONDUCTED AFTER THE 2700 HOUR ENDURANCE RUN

	CLOSING TEST			OPENING TEST		
Breaker Current(a) (Low Voltage) (Amperes)	Time (Milliseconds) Main Contacts	Time (Milliseconds Aux. Contacts	Capacitor Voltage (Volts)	Time (Milliseconds) Main Contacts	Time (Milliseconds) Aux. Contacts	Trip Voltage (Volts)
600	26.0	24.0	55	8.6	9.4 (b) 32.0 (c)	60
800	25.2	23.2	55	7.0	10.0 31.0	60
1000	24.8	23.0	55	6.2	9.0 30.0	60
1200	24.0	22.0	55	7.6	10.0 30.6	60
1400	24.8	23.0	55	8.0	9.6 30.4	60
1600	26.8	24.4	55	7.0	10.0 26.0	60
1800	24.4	23.0	55	6.2	10.0 29.6	60
2000	25.2	23.2	55	7.0	10.0 30.4	60
2000	25.0	23.2	55	8.6	11.6 32.0	60
2400	25.2	23.2	55	8.0	11.6 31.6	60

(a) Inrush current limited. (b) Auxiliary contacts start to open. (c) Mechanism completely open.

TABLE IV

FREE STANDING HEIGHT (INCHES)(1)
OF INCONEL 718 SWITCHGEAR SPRINGS

IDENTITY		PRETEST	POST-TEST
Springs for Mechanism Opening	1.	3.2584	3.209
	2.	3.2648	3.186
	3.	3.2565	3.193
Inside Wipe Springs	1.	1.750	1.720
	2.	1.750	1.744
Outside Wipe Springs	1.	1.825	1.800
	2.	1.825	1.804

Note (1): Measured on a comparator at a point on the spring approximately 90° from end of coil.

TABLE V

LOAD/DEFLECTION DATA OF INCONEL 718 SWITCHGEAR SPRINGS

Identity		Pretest Mechanical Load (lbs)								
Springs for Mechanism Opening	1.	1.9	3.0	4.0	5.1	6.3	7.4	8.4	9.6	10.6
	2.	2.2	3.2	4.2	5.4	6.5	7.5	8.6	9.7	10.7
	3.	2.2	3.1	4.4	5.3	6.5	7.5	8.6	9.6	10.7
Inside Wipe Springs	1.	7.0	11.5	15.5	20.0	24.0	26.0	32.5	36.5	40.5
	2.	7.0	11.5	15.5	20.0	24.0	26.0	32.5	36.5	40.5
Outside Wipe Springs	1.	6.5	12.0	17.5	22.5	28.5	34.0	39.5	45.0	50.0
	2.	6.0	11.5	17.0	22.5	27.5	33.0	38.0	44.0	49.0
		0.2	0.3	0.4	0.5	0.6	0.7	0.8	9.0	1.0

Deflection (1/10ths in.)

Identity		Post-test Mechanical Load (lbs)								
Springs for Mechanism Opening	1.	2.5	3.8	5.0	6.2	7.5	8.8	10.0	11.3	12.8
	2.	2.4	4.0	5.6	7.1	8.6	10.0	11.6	13.2	14.8
	3.	2.4	4.0	5.6	7.1	8.6	10.0	11.6	13.2	14.8
Inside Wipe Springs	1.	7.0	11.5	16.5	21.0	26.0	30.5	35.0*		
	2.	8.0	13.0	17.5	23.0	28.0	33.0	38.0		
Outside Wipe Springs	1.	7.5	14.0	18.0	23.0	27.0	33.0	38.0*		
	2.	8.0	13.0	18.0	23.5	28.5	33.5	39.0*		
		0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0

Deflection (1/10ths in.)

NOTE: Test conducted on a link spring tester S/N 57529 (0-50 lbs).

* - Nominal length.

AC CIRCUIT BREAKER RATED
1000 VOLTS, 600 AMPERES, 1000 Hz, CONTINUOUS
1000 VOLTS, 1800 AMPERES, INTERRUPTION

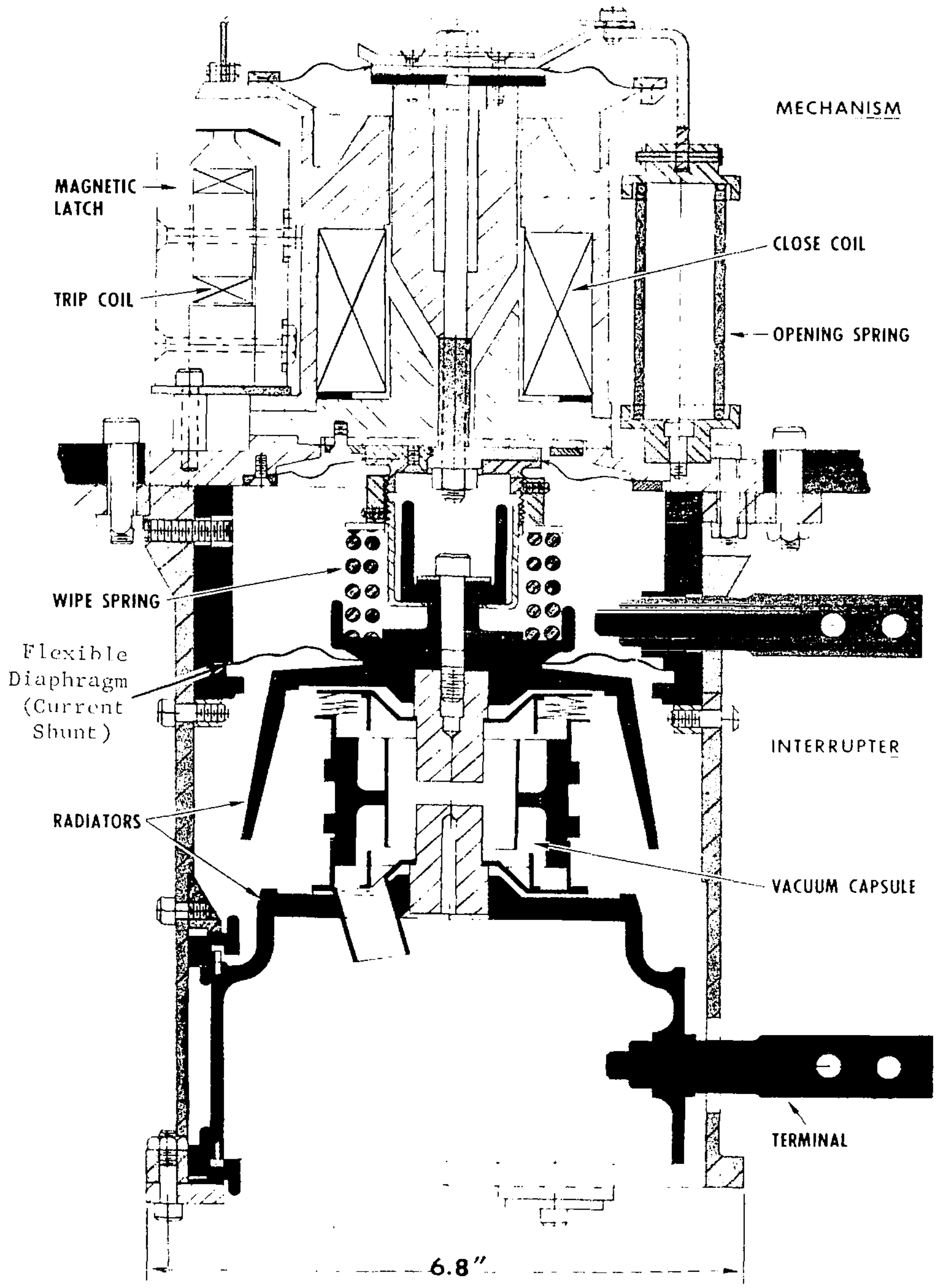


Figure 1. Cross Section Layout of Modified AC Breaker with Flux Shift Latch Mechanism.

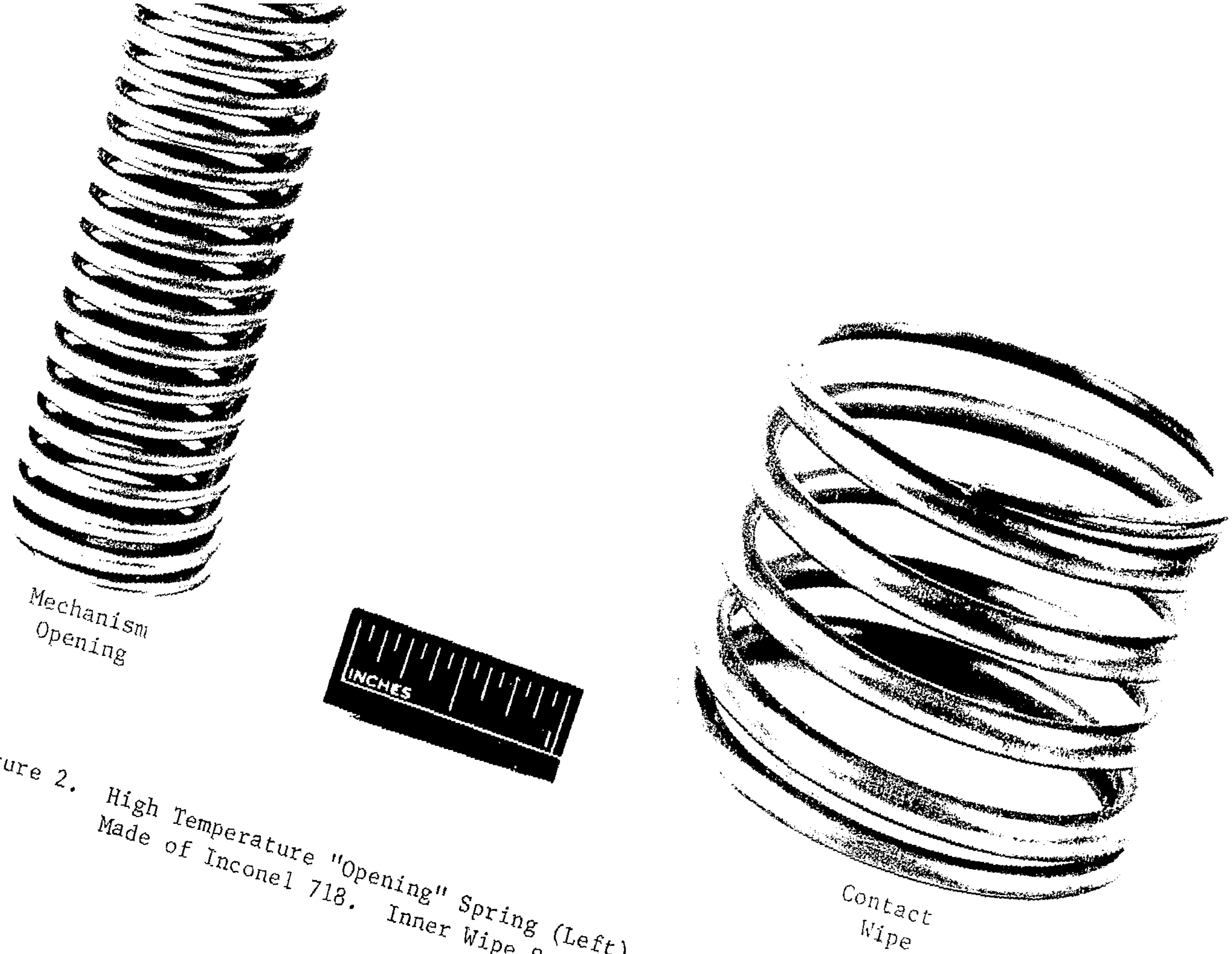


Figure 2. High Temperature "Opening" Spring (Left) and "Outer Wipe" Spring (Right), Made of Inconel 718. Inner Wipe Spring Not Shown.

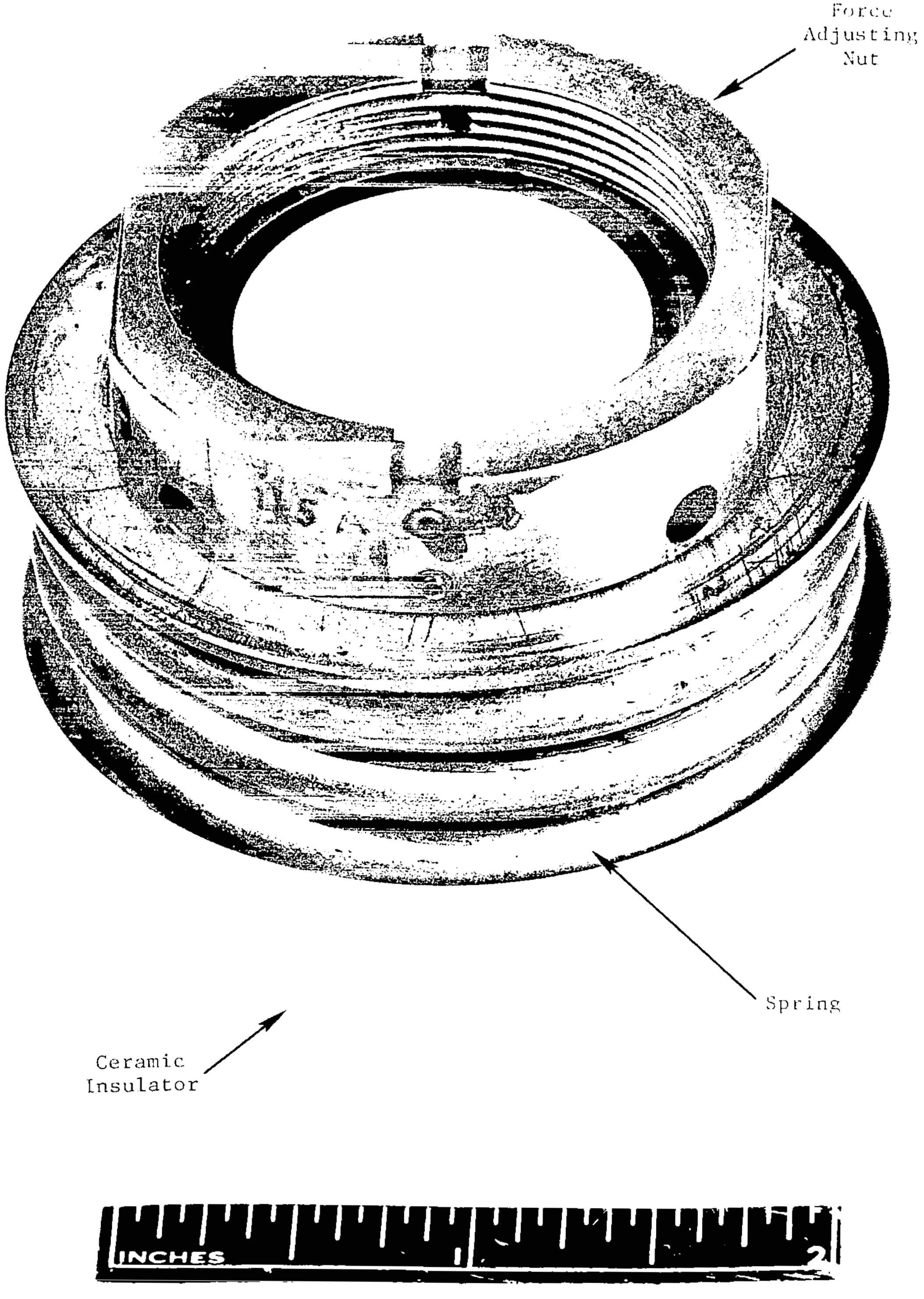


Figure 3. Contact "Wipe" Spring Assembly, with Two High Temperature Compression Springs, for AC Breaker.

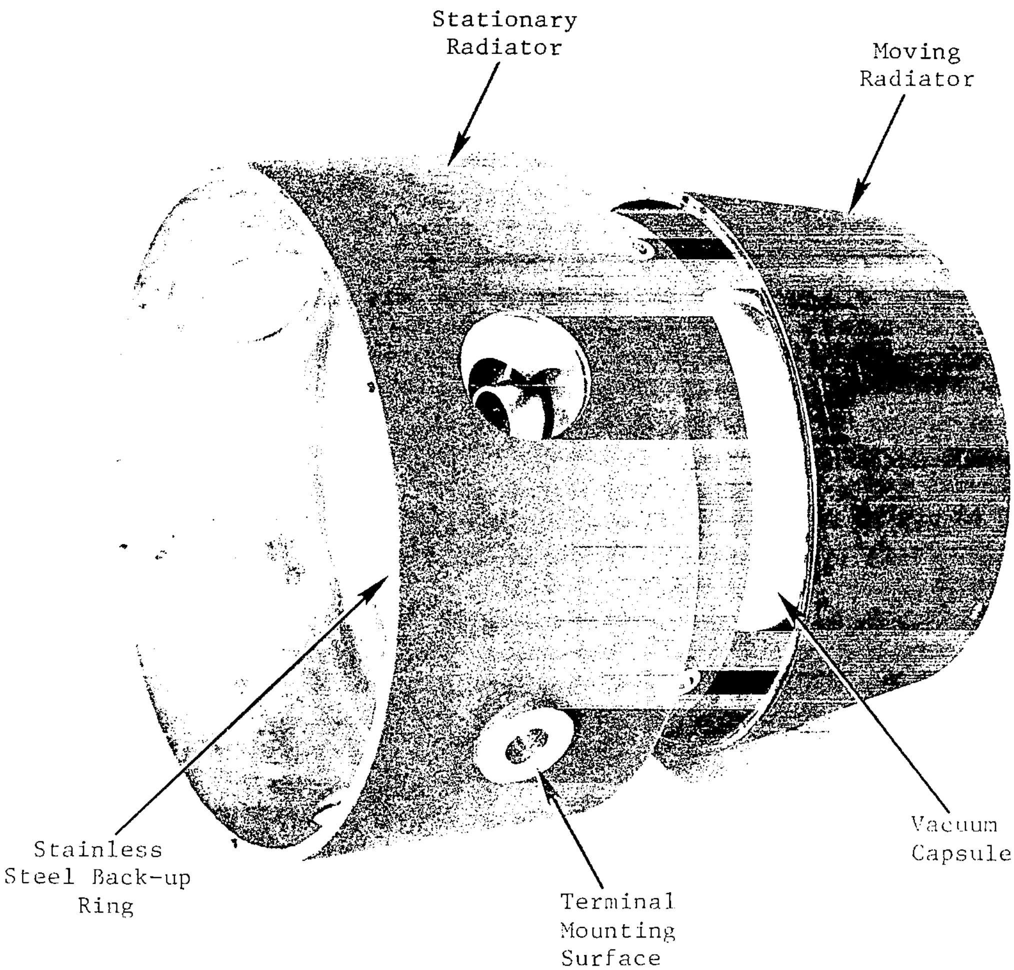


Figure 4. AC Breaker Contact (Vacuum) Capsule with Radiators Attached and Before Evacuation and Seal-Off.

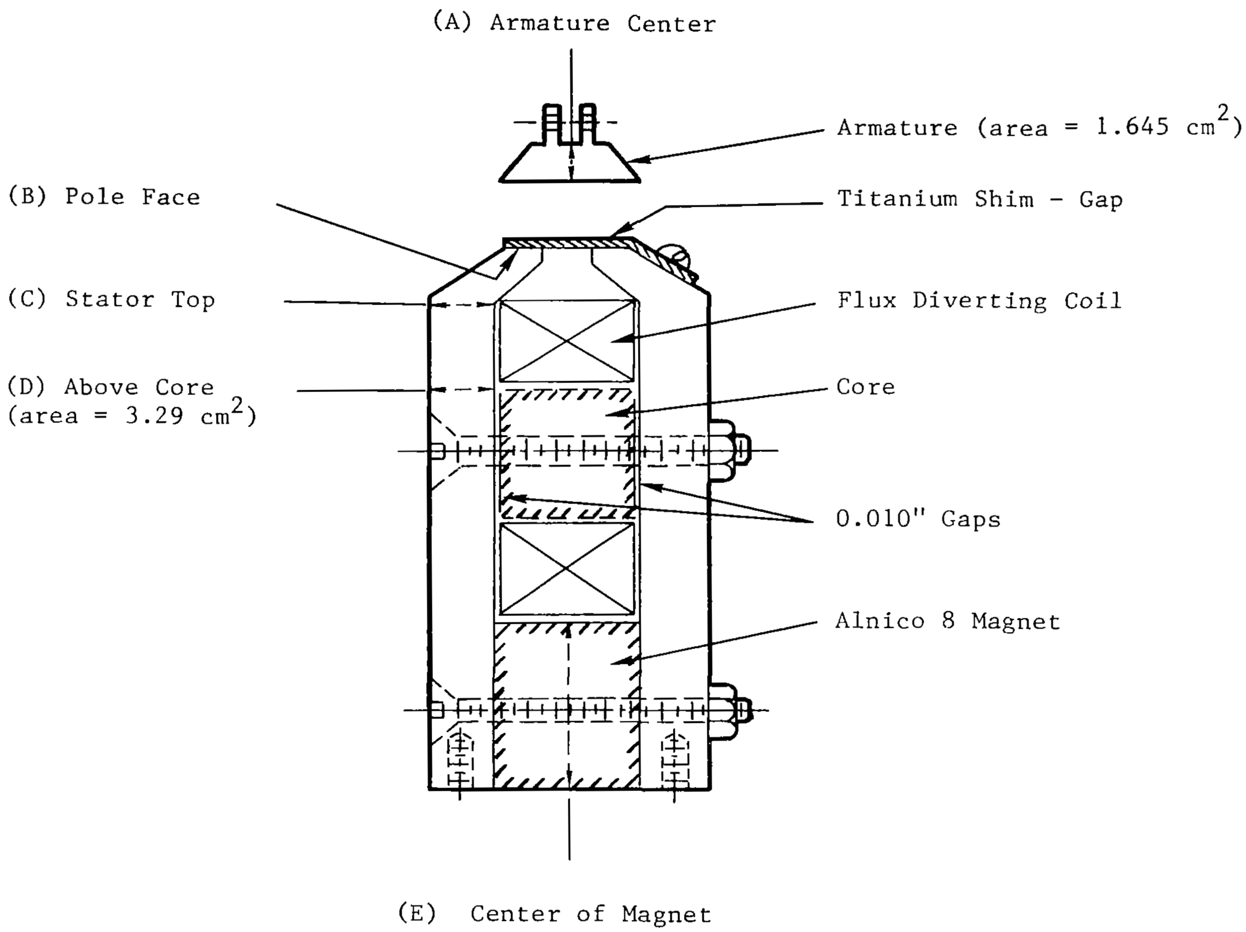


Figure 5. Sketch of Magnetic Flux Shift Latch Structure.

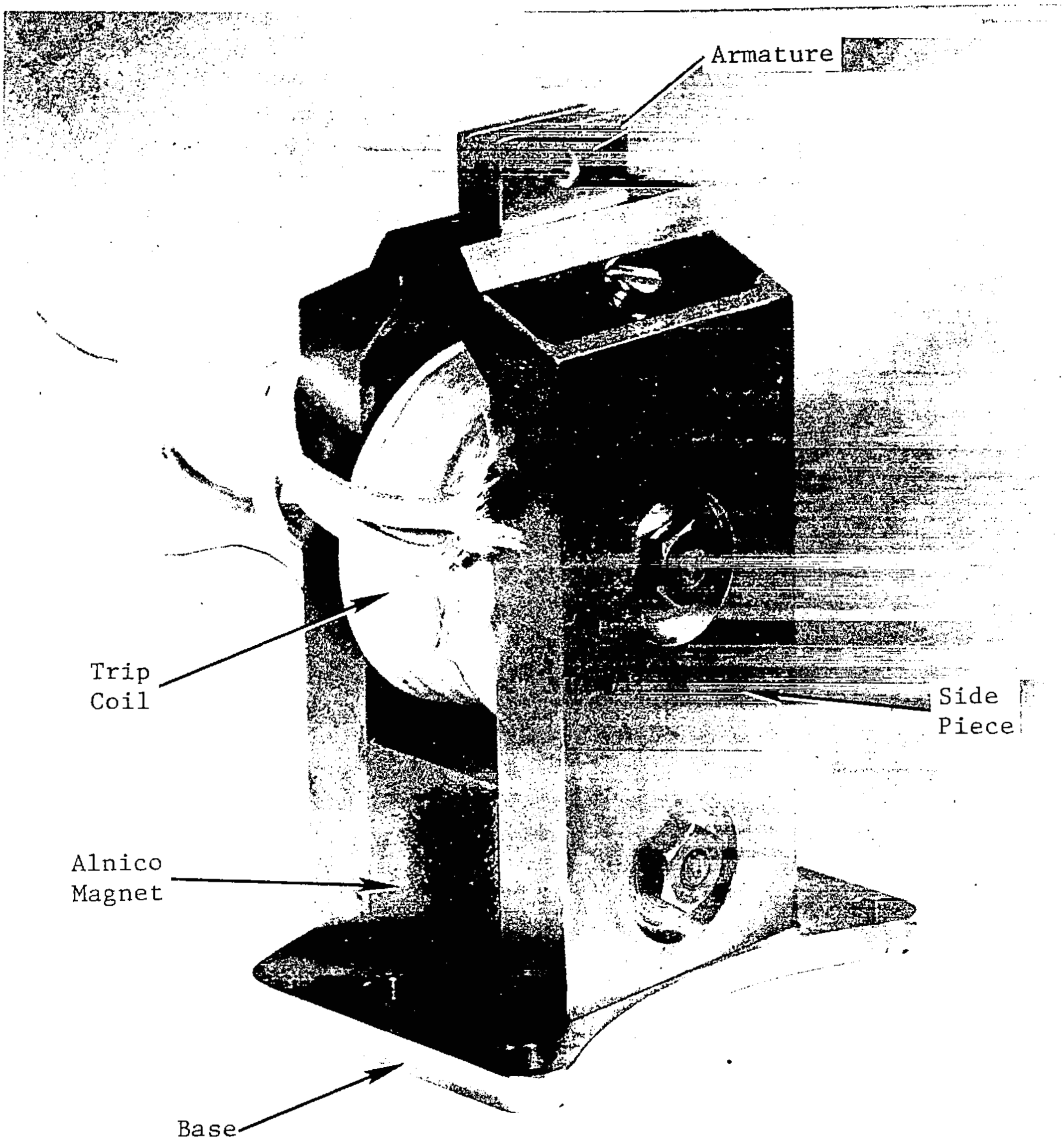


Figure 6. Flux Shift Latch Used in Redesigned Mechanism, Assembled with High Temperature Coil and Alnico 8 Magnet.

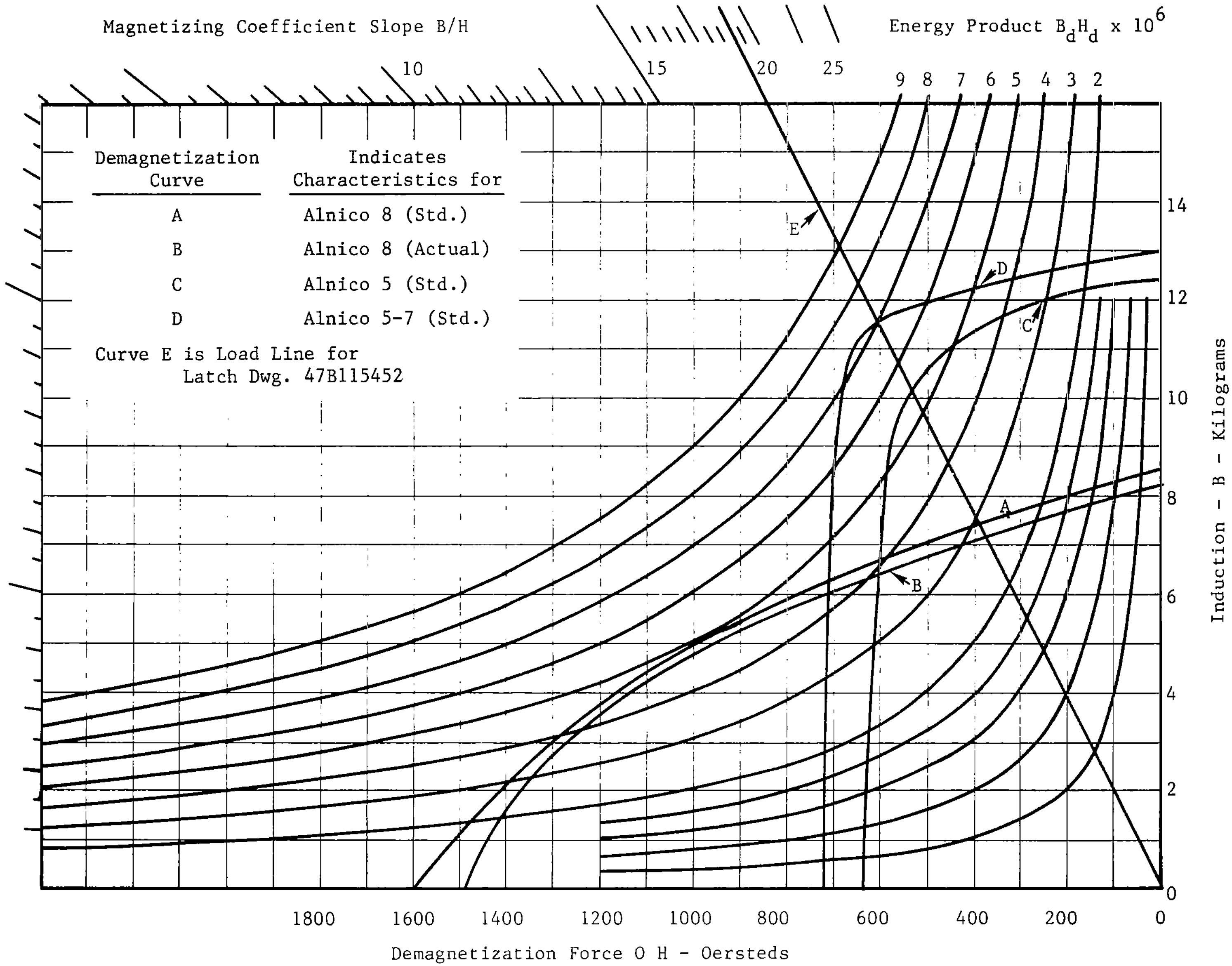


Figure 7. Demagnetization and Energy Product Information Curves for Flux Shift Latch with Various Alnico Magnets.

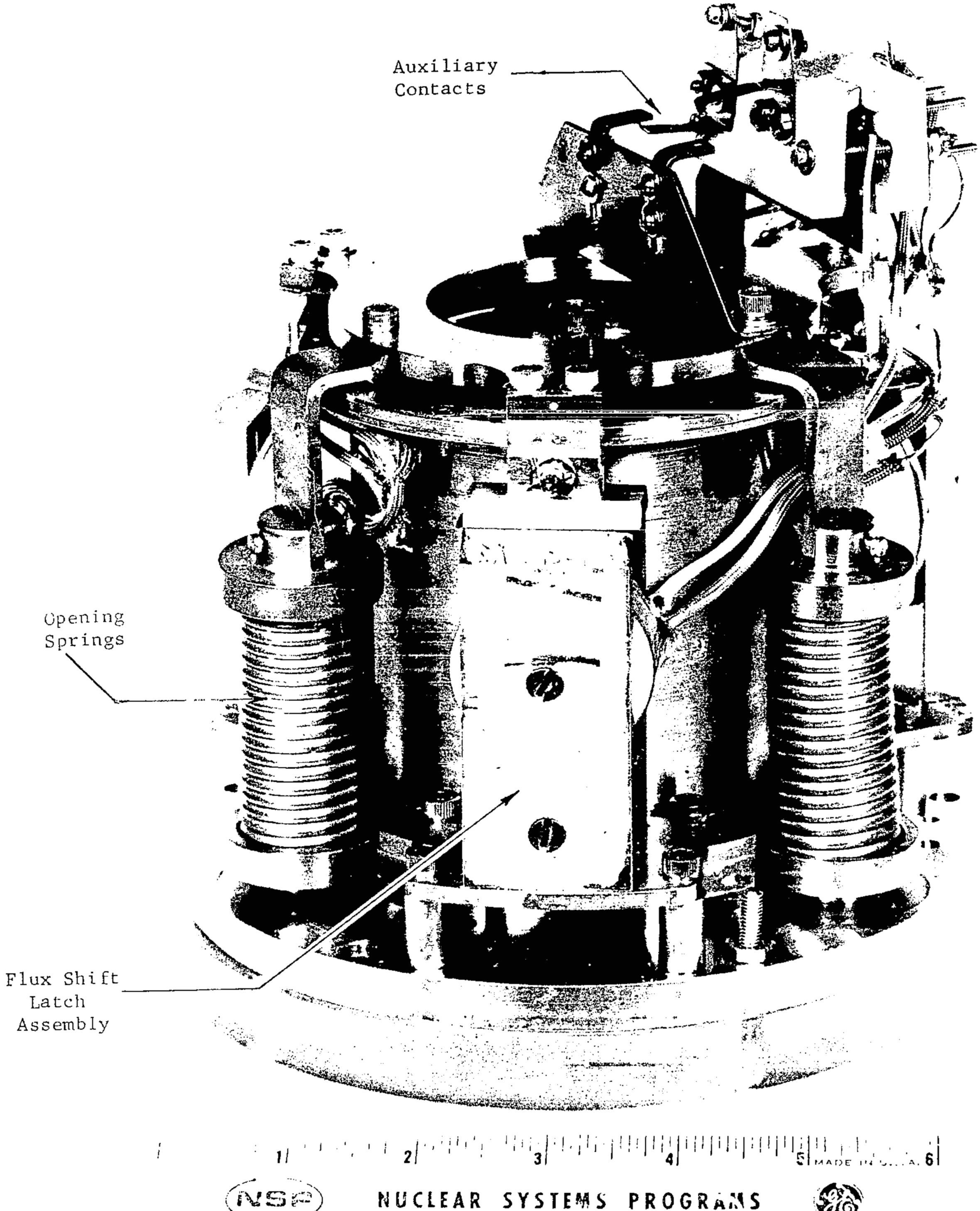


Figure 8. Mechanism After Final Modifications with Stiffer Support for Latch Armatures, and Greater Clearance for Closing Solenoid Armature.

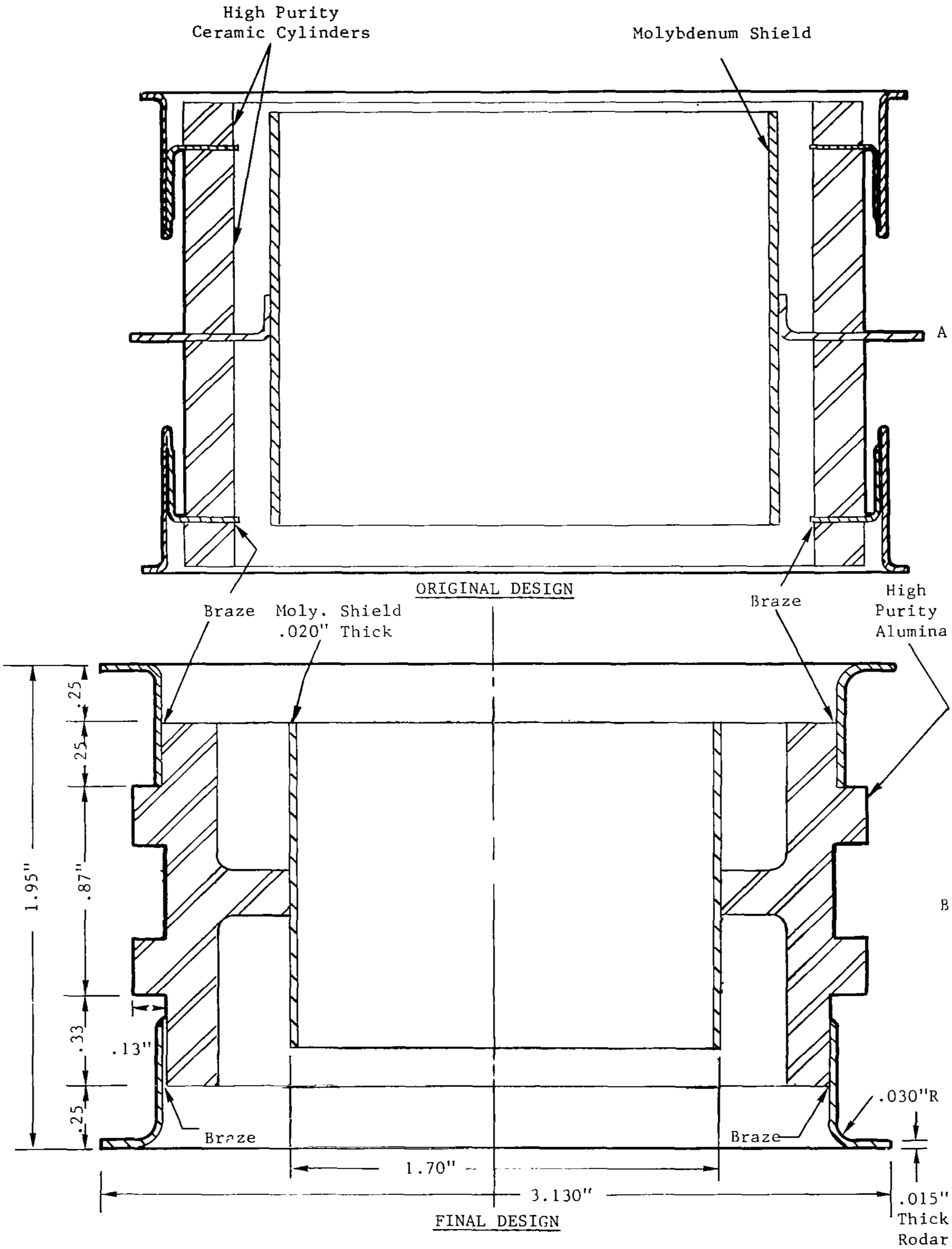


Figure 9. Cross Section Layout of Contact Capsule Ceramic Assembly.

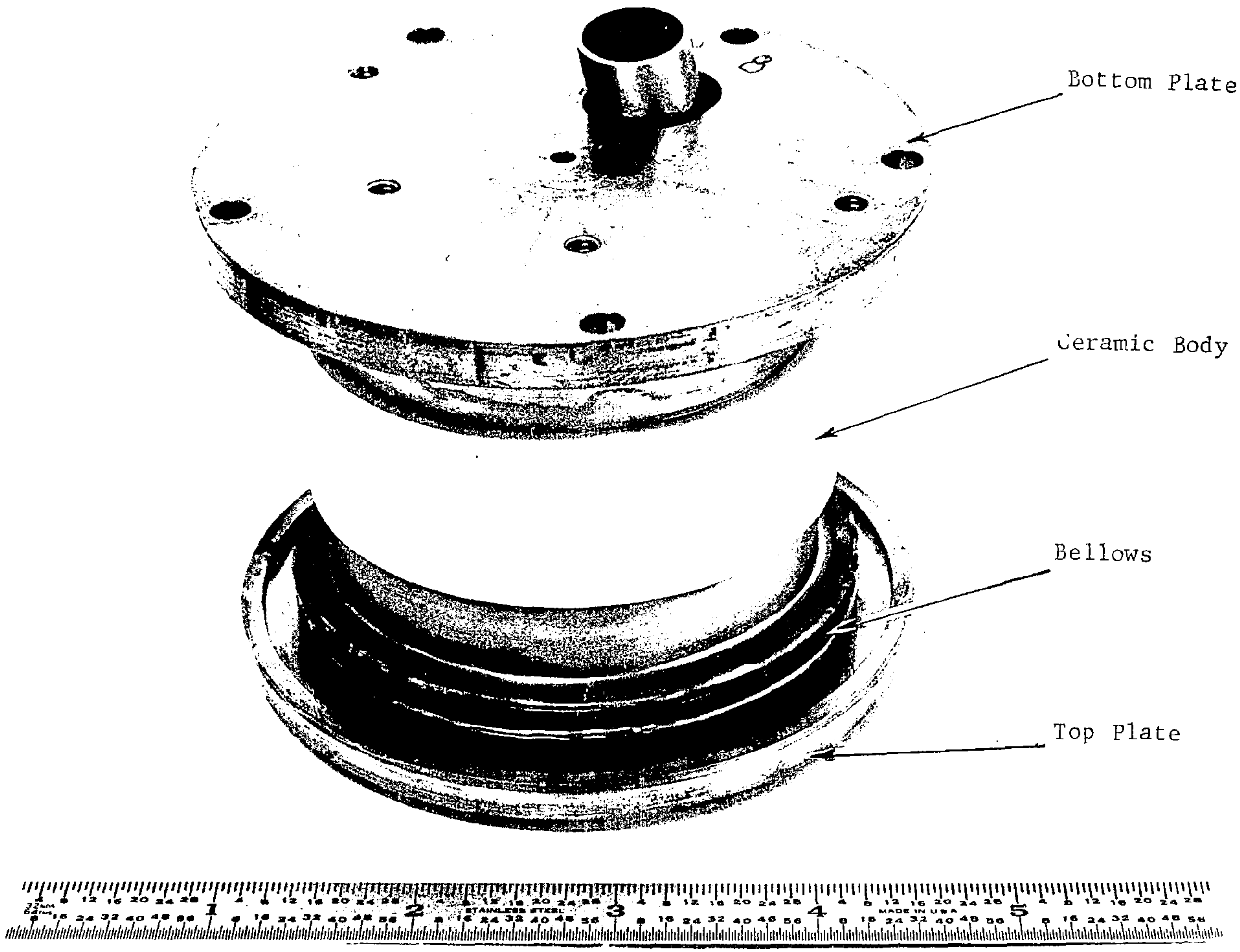


Figure 10. Completely Assembled Vacuum Contact Capsule, Before Evacuation and Seal-Off.

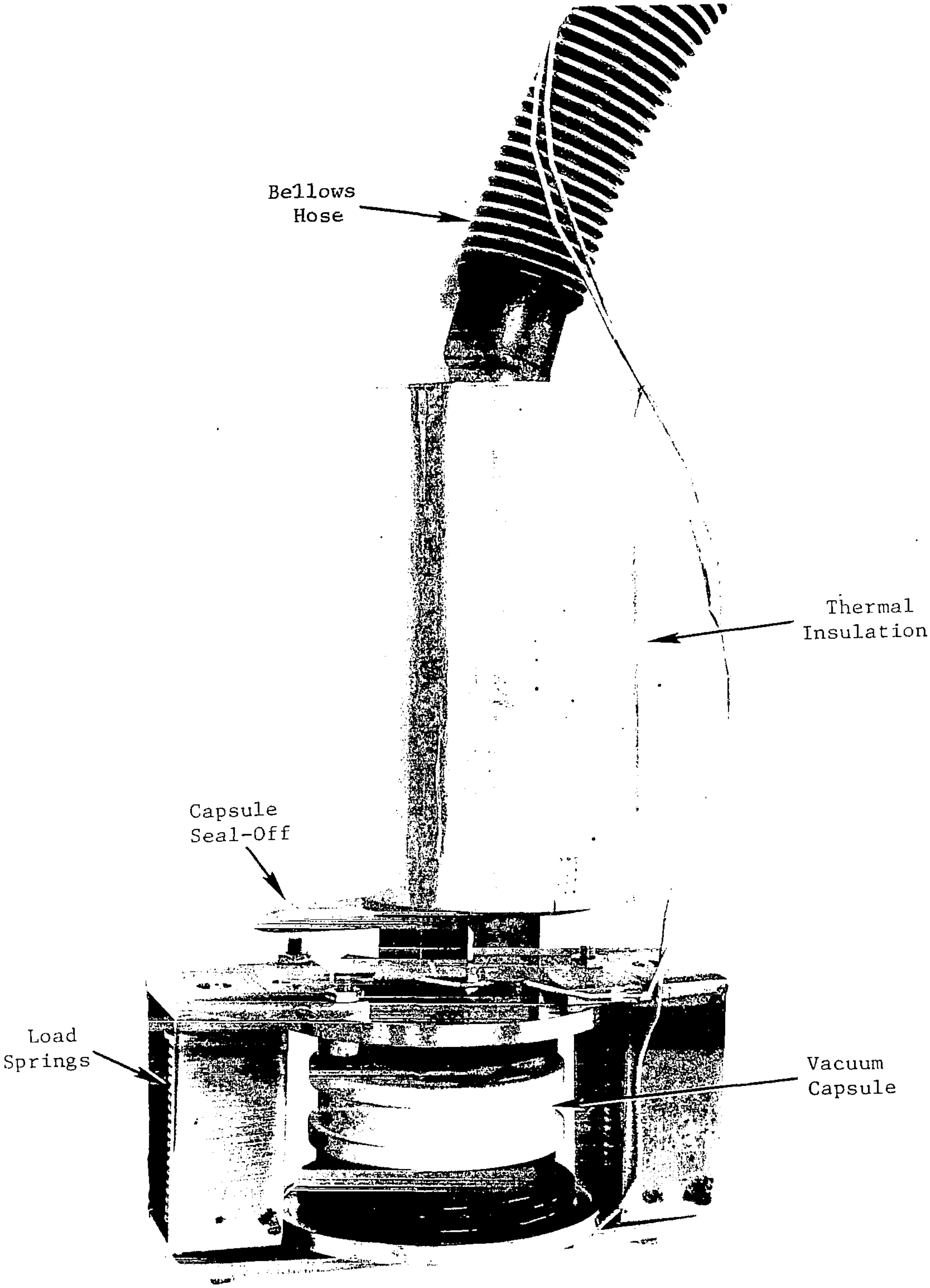


Figure 11. Sealed Vacuum Contact Capsule with Attached 0.5 Liter/Second Ion Pump and Heat Shield, Contacts Held Closed by Spring Loaded Fixture.

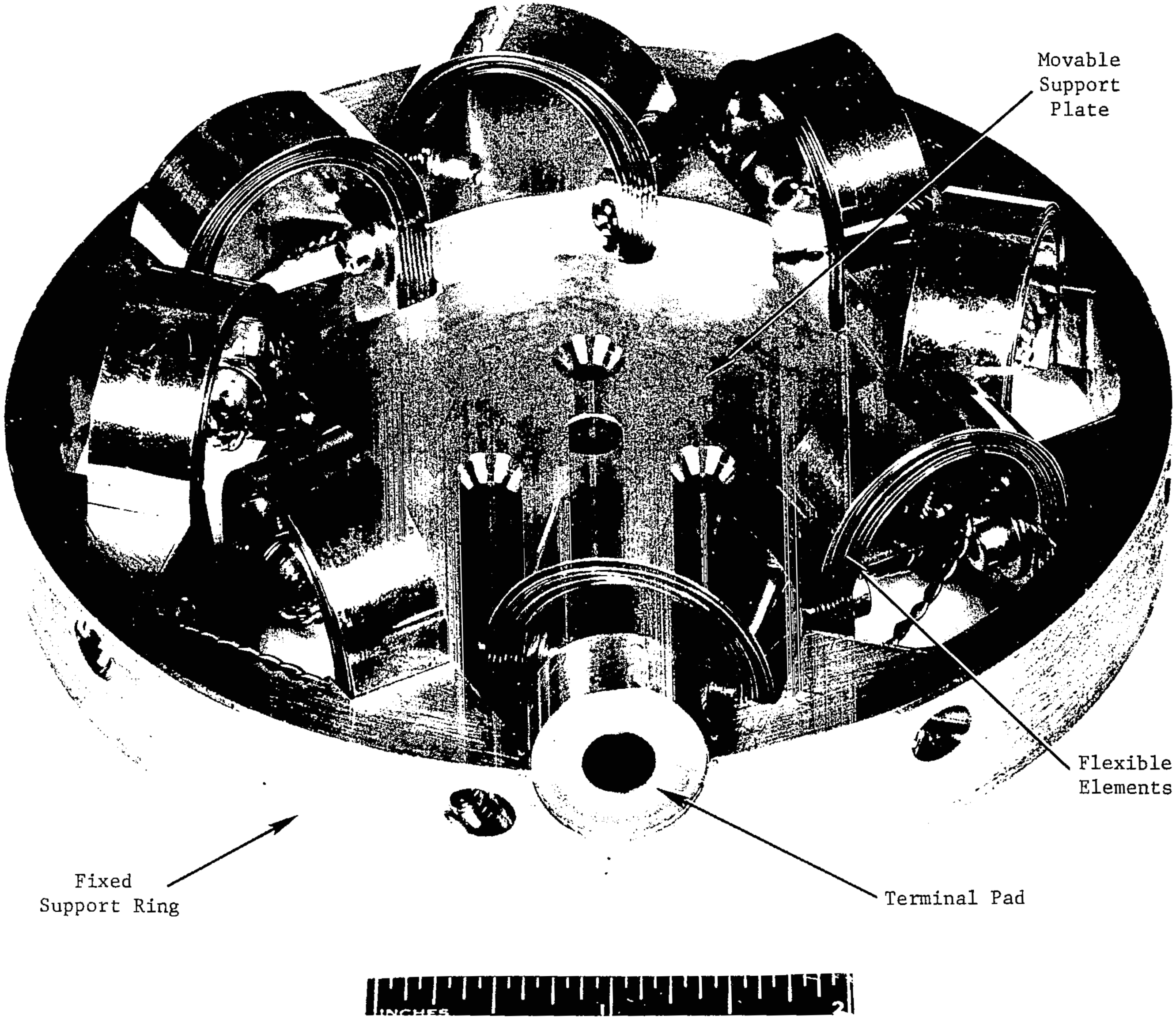


Figure 12. New Current Carrying Shunt with Multiple 0.006-Inch Thick Cube-Alloy Flexible Strips for the AC Breaker.

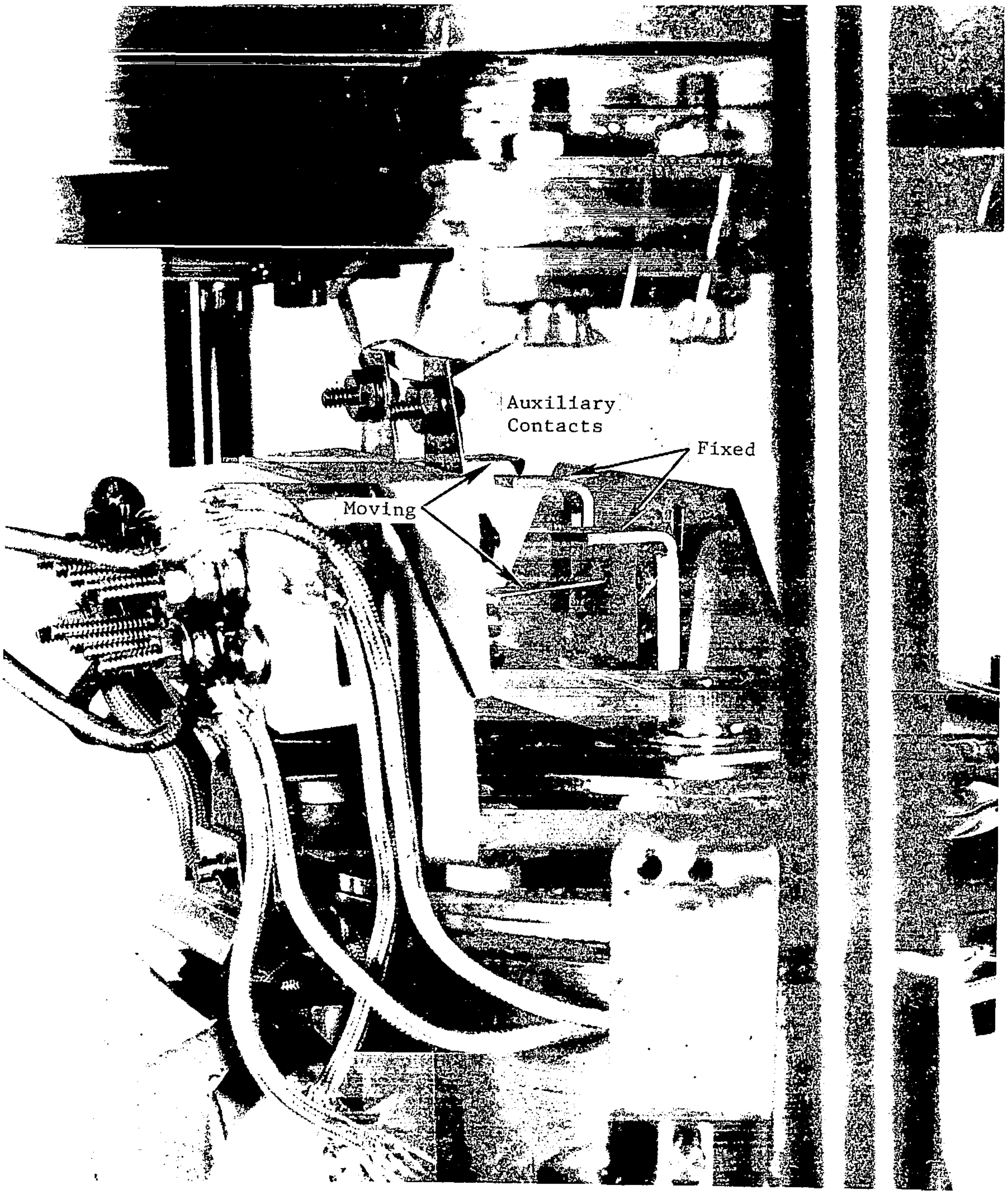


Figure 13. AC Breaker Auxiliary Contacts and Coil Lead Terminal Board.

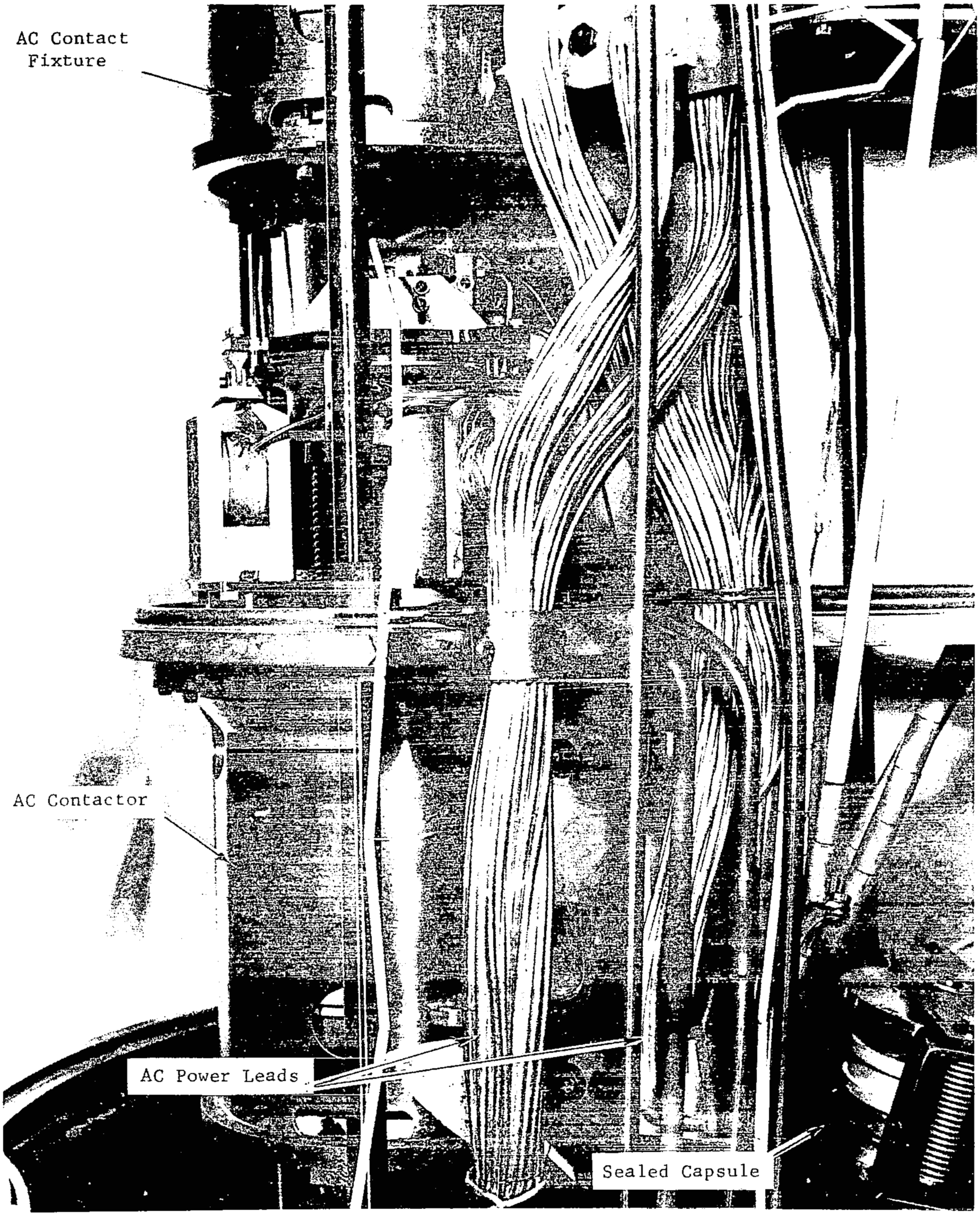


Figure 14. AC Breaker and Mechanism with Final Modifications, Ready for Endurance and Rated Interruption Power Tests.

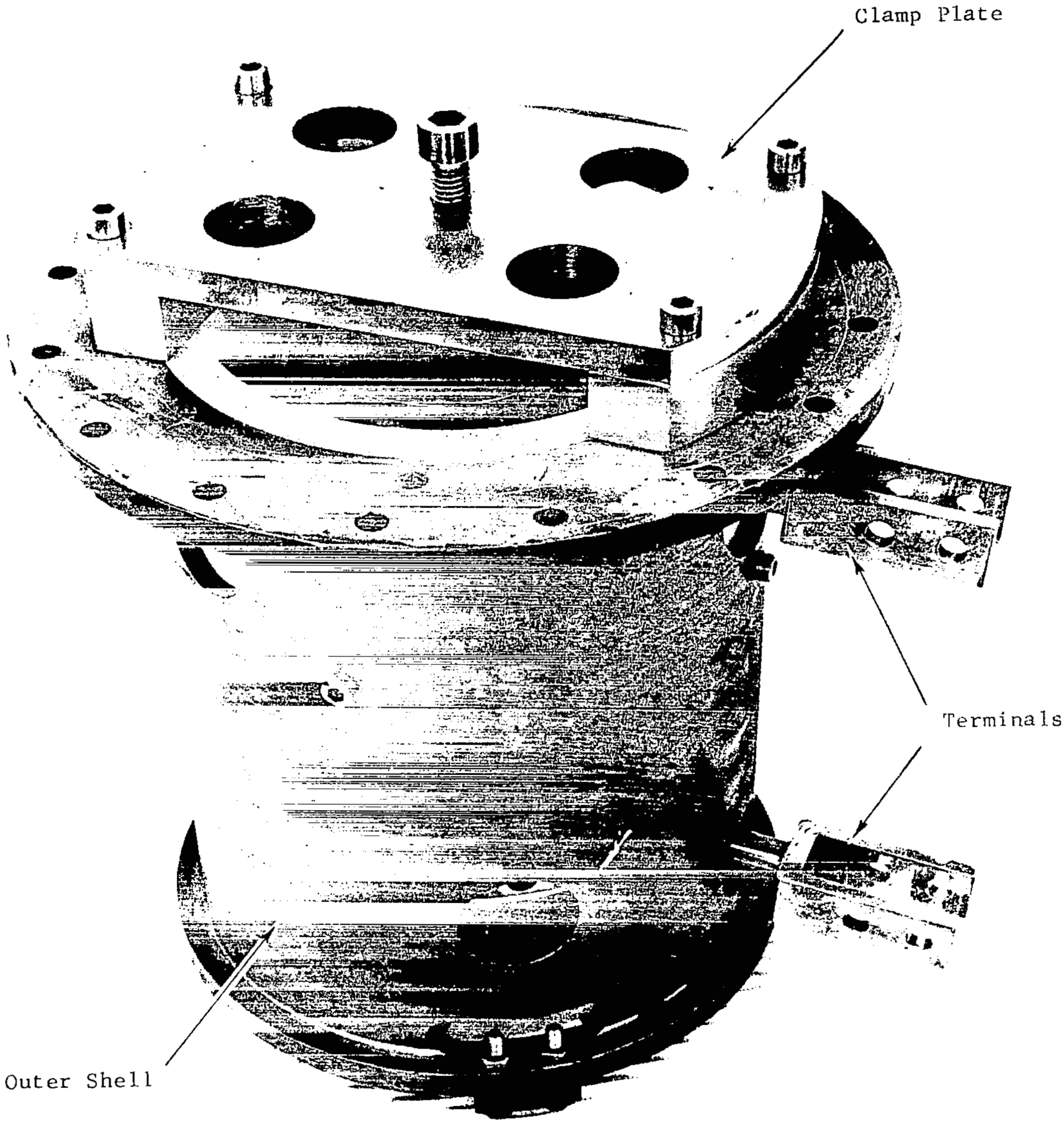
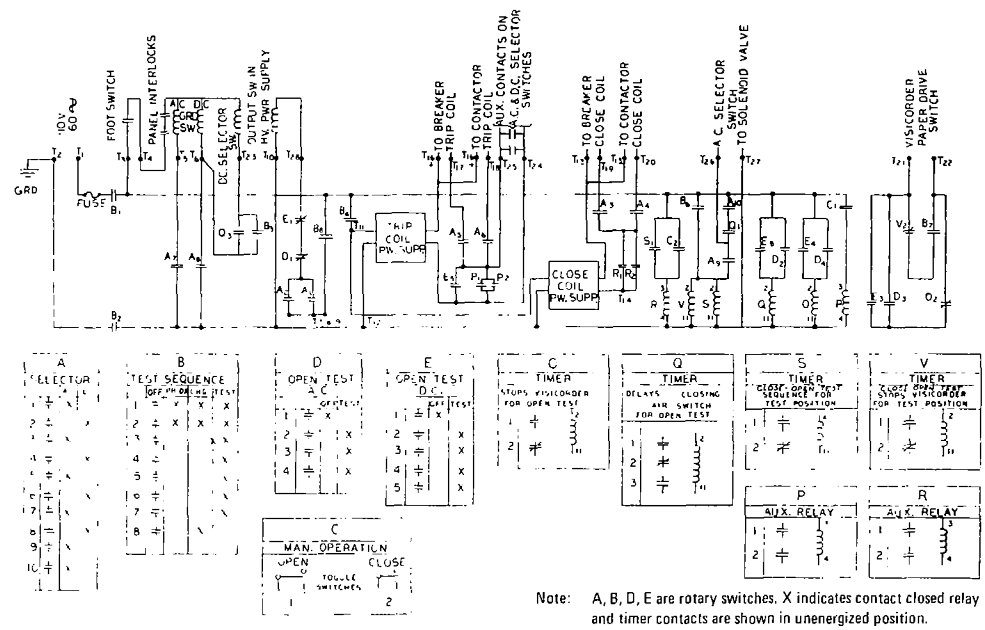


Figure 15. AC Contact Fixture, Including Interrupter Unit, with Contact Capsule, Terminals, and Contact Wipe Spring Pressure Plate.



Note: A, B, D, E are rotary switches. X indicates contact closed relay and timer contacts are shown in unenergized position.

AC "CLOSE–OPEN" TEST

1. Energize Control Unit
2. Selector Switch "A" to AC
3. Step on Foot Switch (Completes Interlock Circuit)
4. Test Sequence "B" Switch Movement from OFF to:
   - PR. ON AC grounding switch picks up.
   - CHARGE Both "Close" and "Trip" coil power supplies are energized. Output switch in high voltage DC power supply is closed, thus charging the capacitors.
   - TEST POSITION
     a. Energizes AC trip coil, thus breaker will not hold itself closed.
     b. Energizes timers S & V. Timer "S" delays the closing of the breaker for a predetermined time. Then the breaker closes and opens.
     c. Timer "V", recorder drive timer, starts the recorder immediately and shuts it off after a preset time.

DC "CLOSE–OPEN" TEST

1. Energize Control Unit
2. Selector Switch "A" to DC
3. Step on Foot Switch (Completes Interlock)
4. Test Sequence "B" Switch Movement from OFF to:
   - PR. ON DC grounding switch picks up.
   - CHARGE Both "Close" and "Trip" coil power supplies are energized, and test capacitors are being charged.
   - TEST POSITION
     a. Energizes DC trip coil, thus contactor will not hold itself closed.
     b. Energizes timers S & V. Timer "S" delays the closing of the contactor for a predetermined time. Then the contactor closes and opens.
     c. Timer "V", recorder drive timer, starts the recorder immediately and shuts it off after a preset time.

AC "OPEN" TEST

1. Energize Control Unit
2. Selector Switch "A" to AC
3. Step on Foot Switch (Completes Interlock)
4. Test Sequence "B" Switch Movement from OFF to:
   - PR. ON AC grounding switch picks up.
   - CHARGE Both "Close" and "Trip" coil power supplies are energized. Power capacitors are being charged.
5. MAN – OPERATION – TOGGLE SWITCH TO CLOSE POSITION – Breaker Closes.
6. MOVE TEST AC SWITCH FROM OFF TO:
   - TEST
     a. Opens output switch in high voltage supply.
     b. Closes timer "Q" which delays the closing of the air operated AC selector switch (when air switch closes its auxiliary switch trips the breaker to open).
     c. Visicorder starts immediately and timer "O" shuts off visicorder after a preset time.

DC "OPEN" TEST

1. Energize Control Unit
2. Selector Switch "A" to DC
3. Step on Foot Switch (Completes Interlock)
4. Test Sequence "B" Switch Movement from OFF to:
   - PR. ON DC grounding switch pickup.
   - CHARGE Both "Close" and "Trip" coil power supplies are energized.
5. MAN – OPERATION – TOGGLE SWITCH TO CLOSE POSITION – Contactor Closes.
6. MOVE TEST DC SWITCH FROM OFF TO:
   - TEST
     a. Opens output switch in high voltage power supply.
     b. Closes DC selector switch.
     c. Starts visicorder.
     d. Starts timer for stopping visicorder.
     e. Auxiliary contacts on selector switch closes the trip coil, contactor opens, and timer "O" shuts off visicorder after a preset time.

Figure 16. Interruption Test Control Circuit Diagrams and Test Operating Sequence Data.

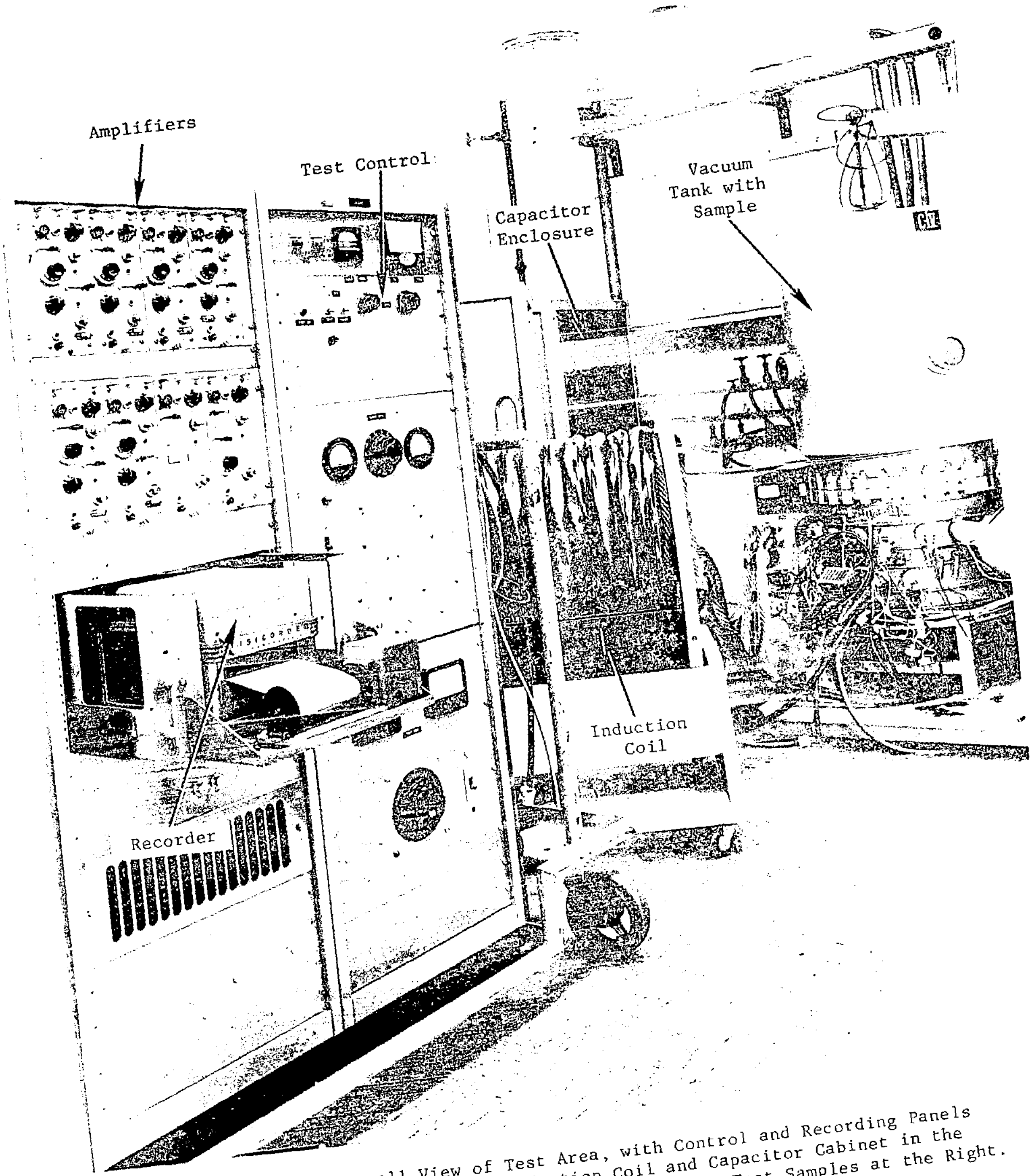


Figure 17. Overall View of Test Area, with Control and Recording Panels at the Left, AC Induction Coil and Capacitor Cabinet in the Far Center, and Vacuum Tank with the Test Samples at the Right.

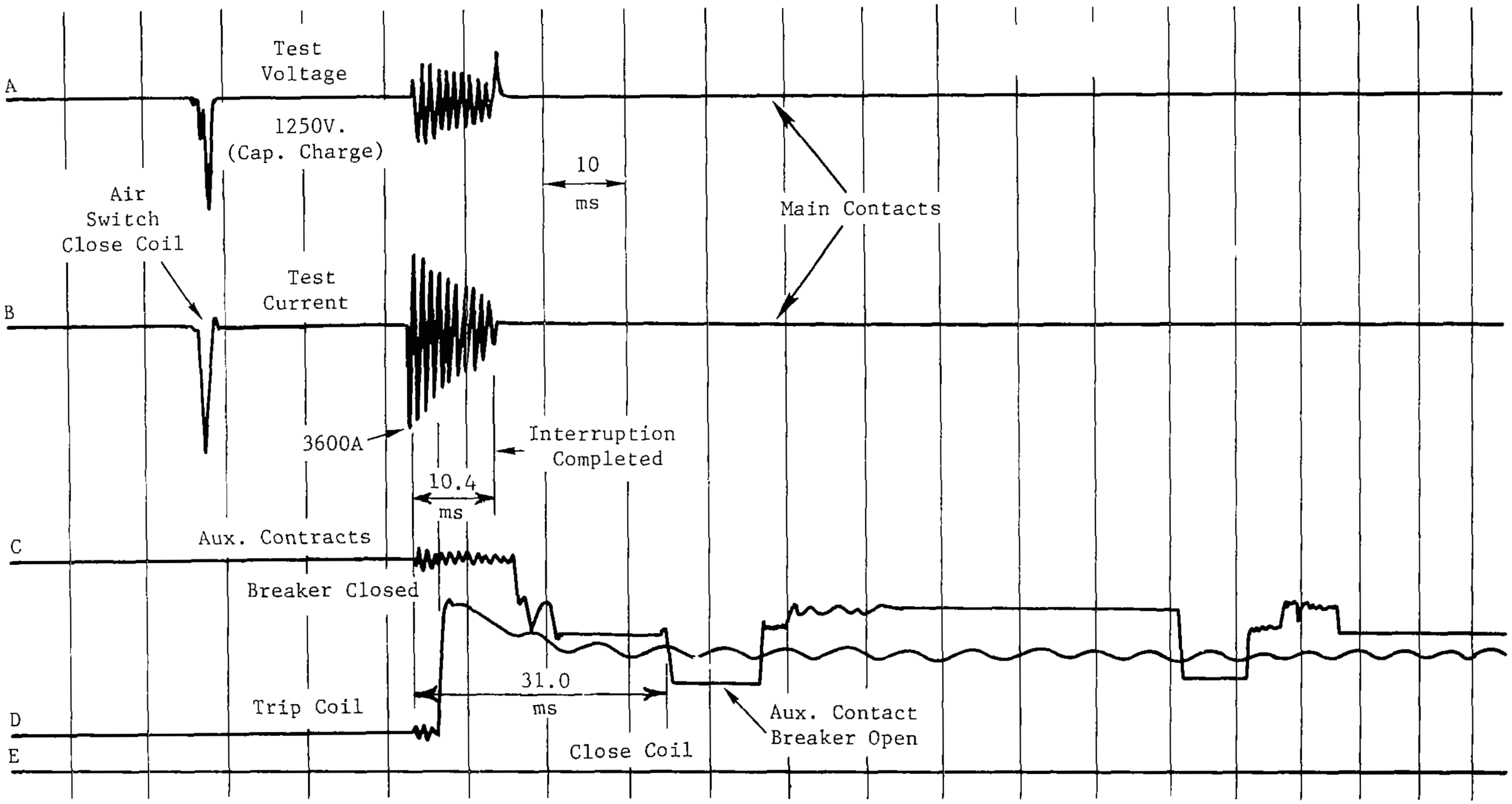


Figure 18. Copy of Visicorder Record of "Open Only" Interruption Test with the AC Breaker at 1000°F, in Vacuum, in a Circuit Providing an Initial Peak of 1250 V and 3600 A. (Test #9)

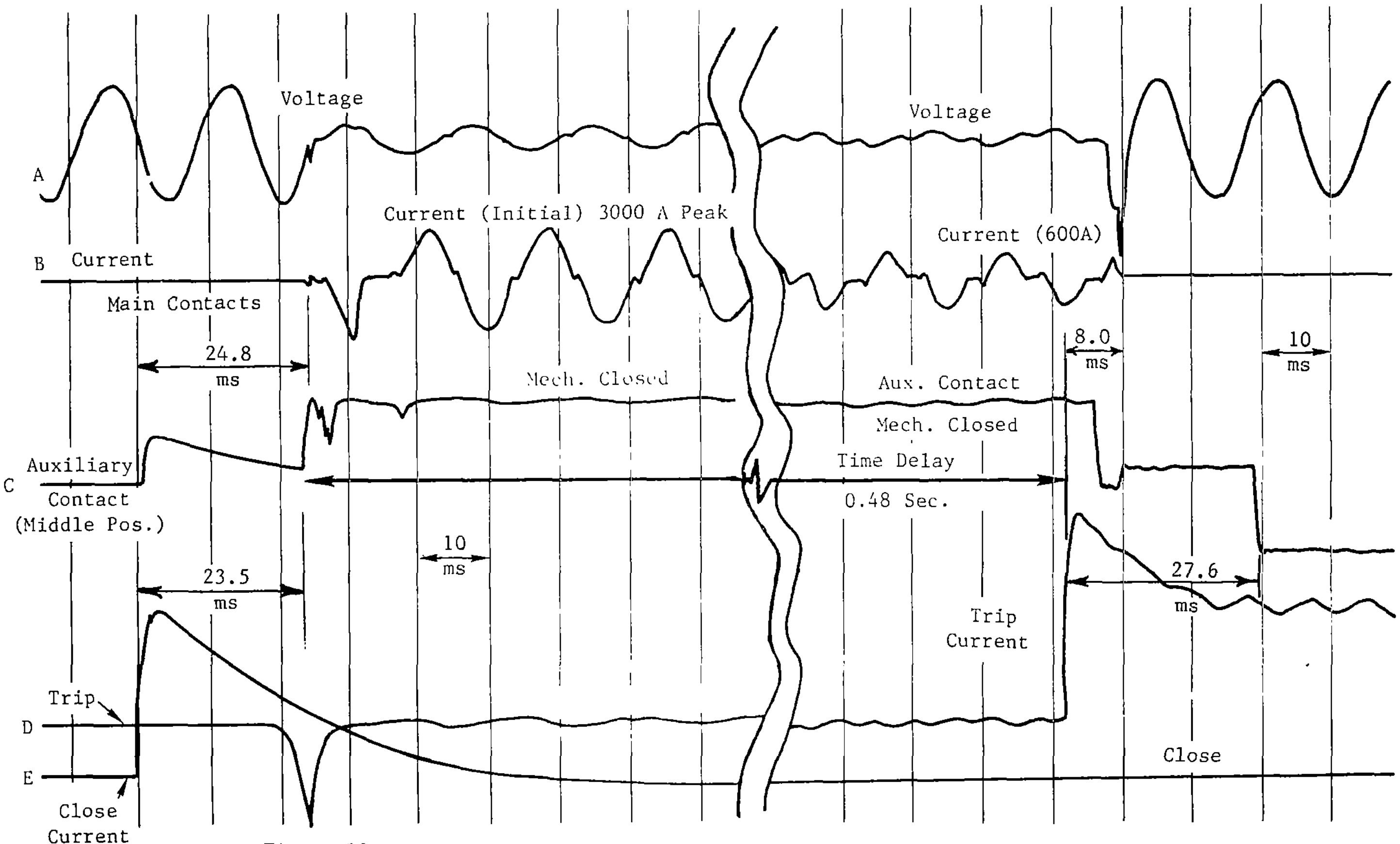


Figure 19. Copy of Part of Visicorder Record of a Typical Close-Open 600 A Switching Test with the AC Breaker at 1000°F, in Vacuum, in a Low Voltage Circuit with an Inrush Current of Approximately 3000 A peak.

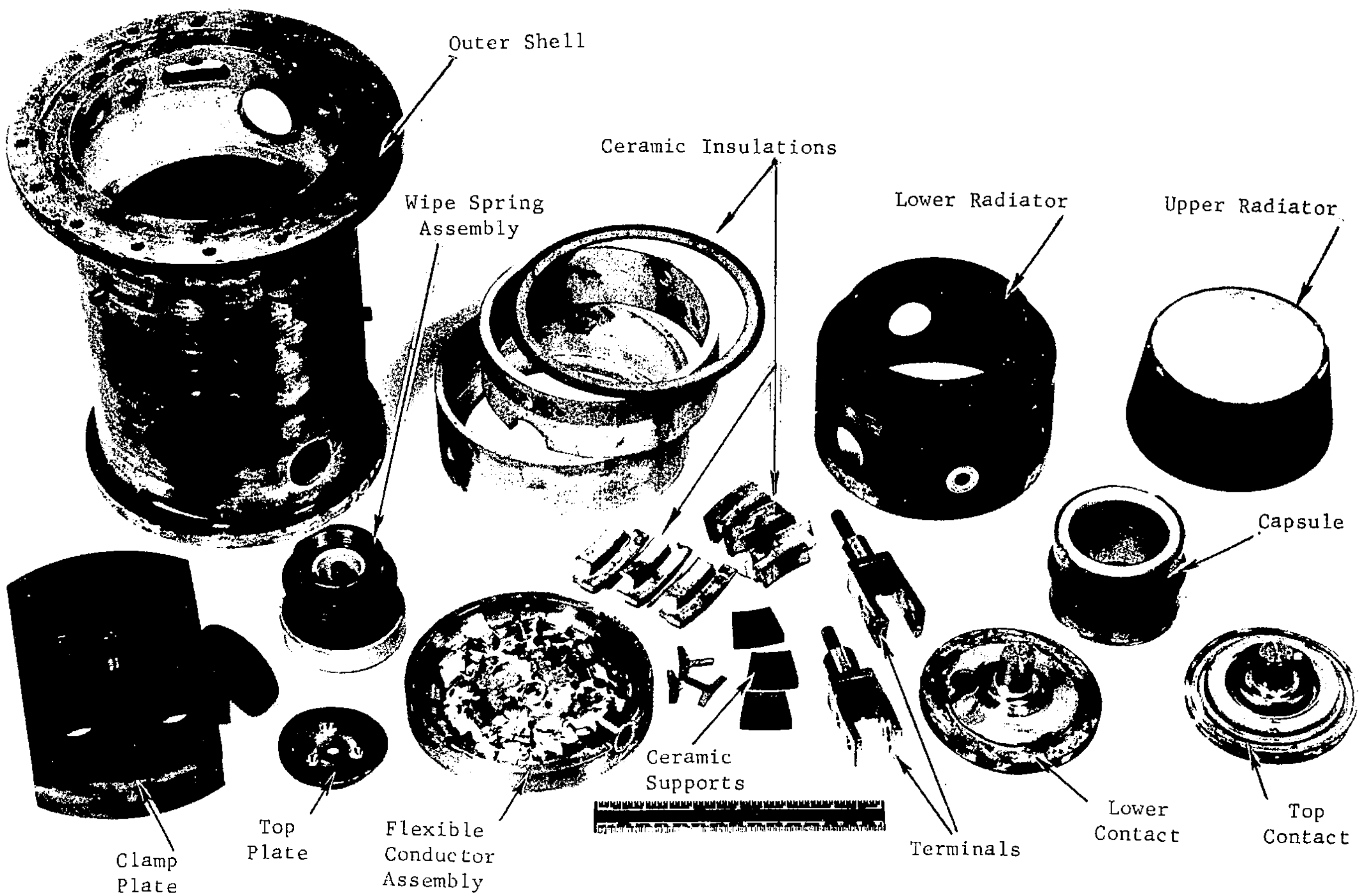


Figure 20. AC Contact Fixture Parts After Dismantling, Following 2700-Hour Endurance Test.

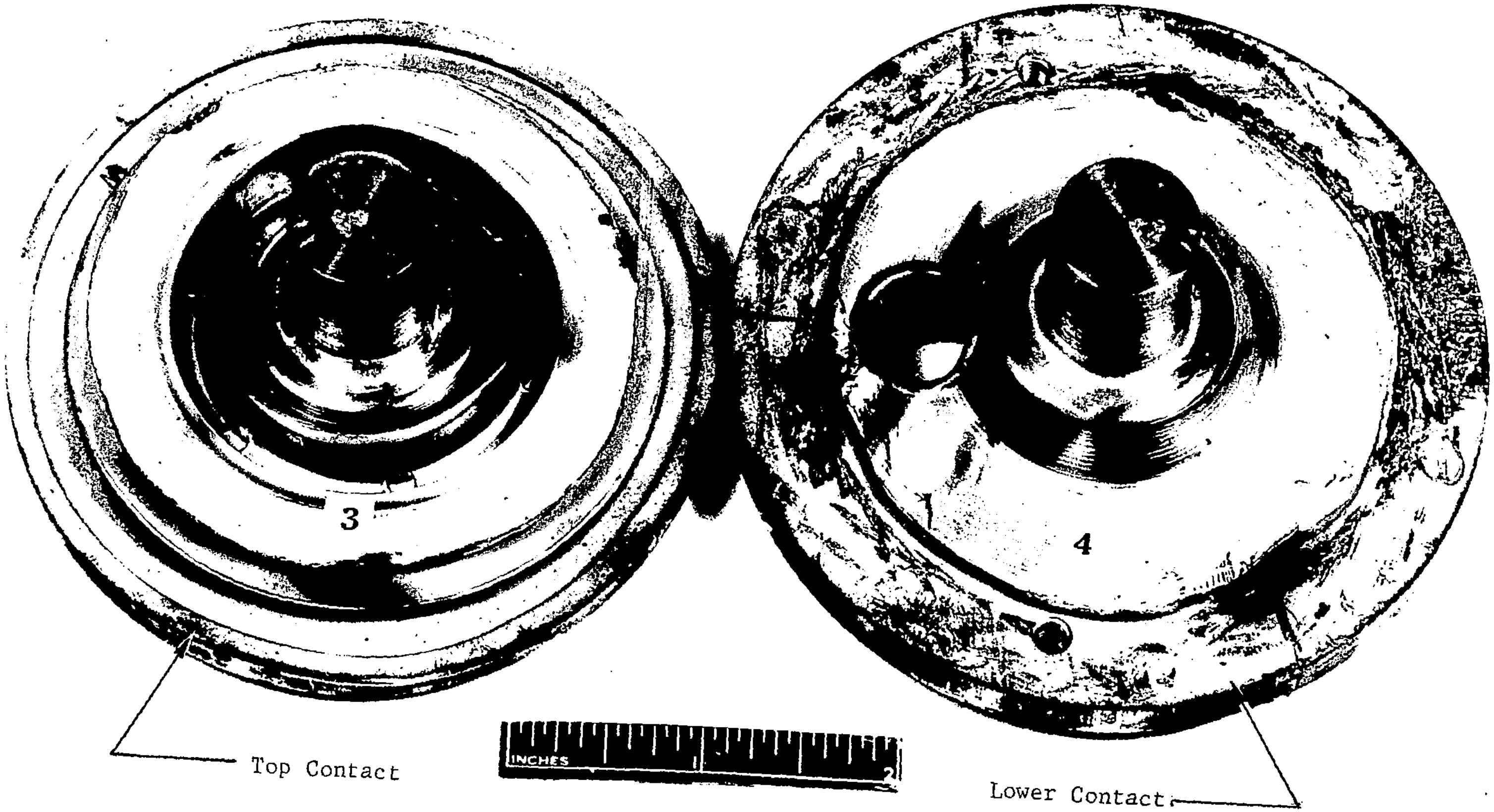
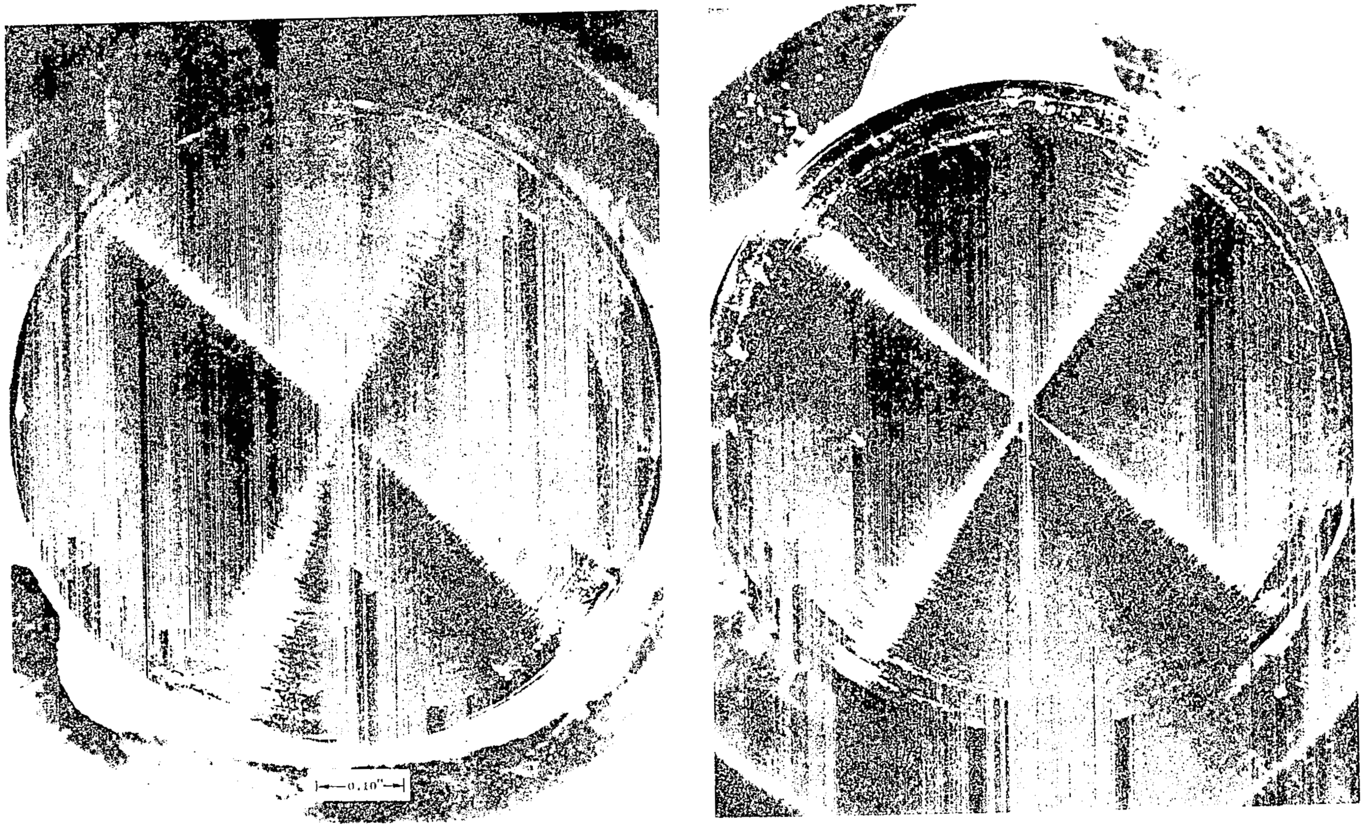


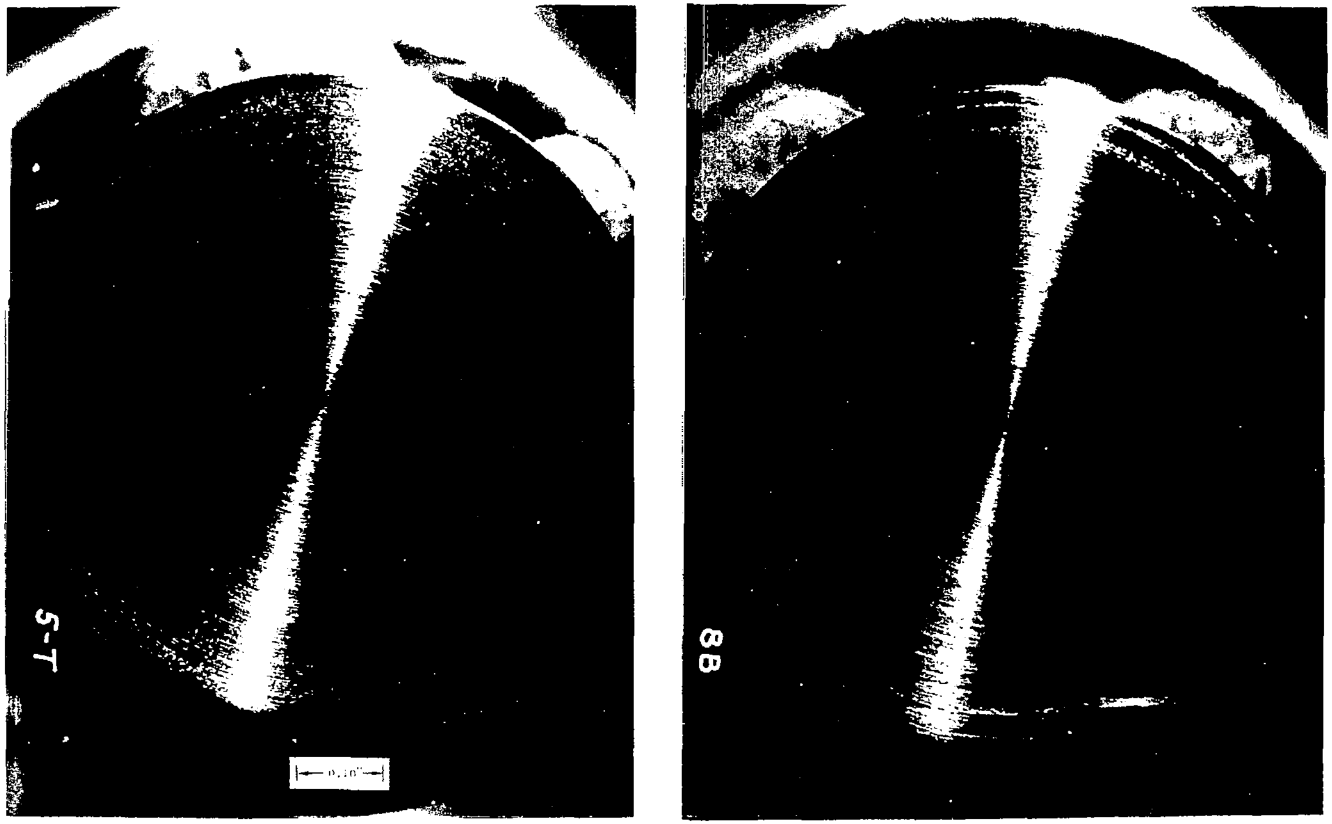
Figure 21. AC Contact Fixture Capsule End Flanges with the Molybdenum Contact Surfaces Showing Slight Pitting from Passage of Test Current While in Closed Position.



a. Top Contact

b. Bottom Contact

Figure 24. Sealed Capsule Contact Surfaces (Magnified) Showing Only Slight Scratches Caused by Mechanical Movements During Assembly.



a. Top Contact

b. Bottom Contact

Figure 25. Sealed Capsule Contact Surfaces Before Assembly and Test.

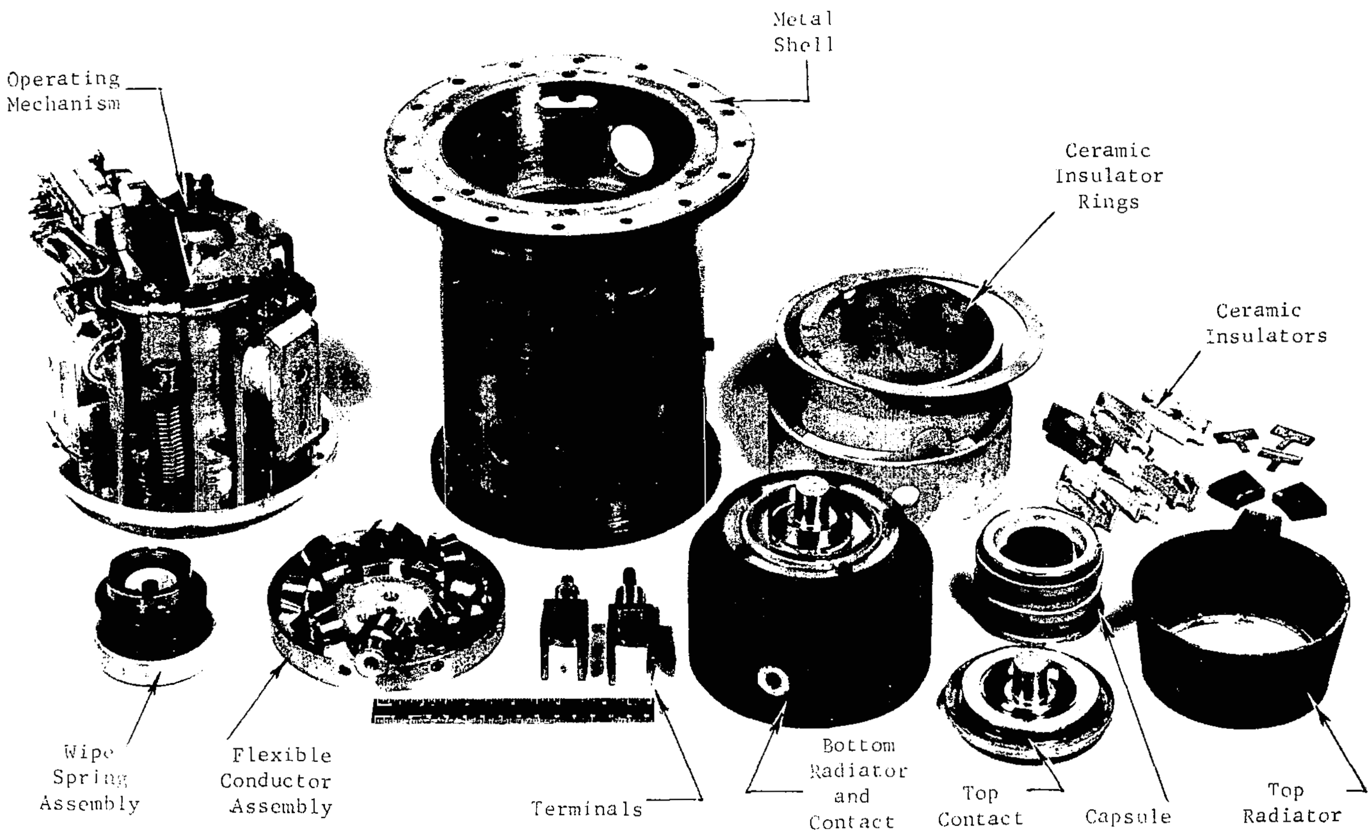


Figure 26. AC Breaker Parts After Dismantling, Following 2700-Hour Endurance, Switching, and Interruption Tests.

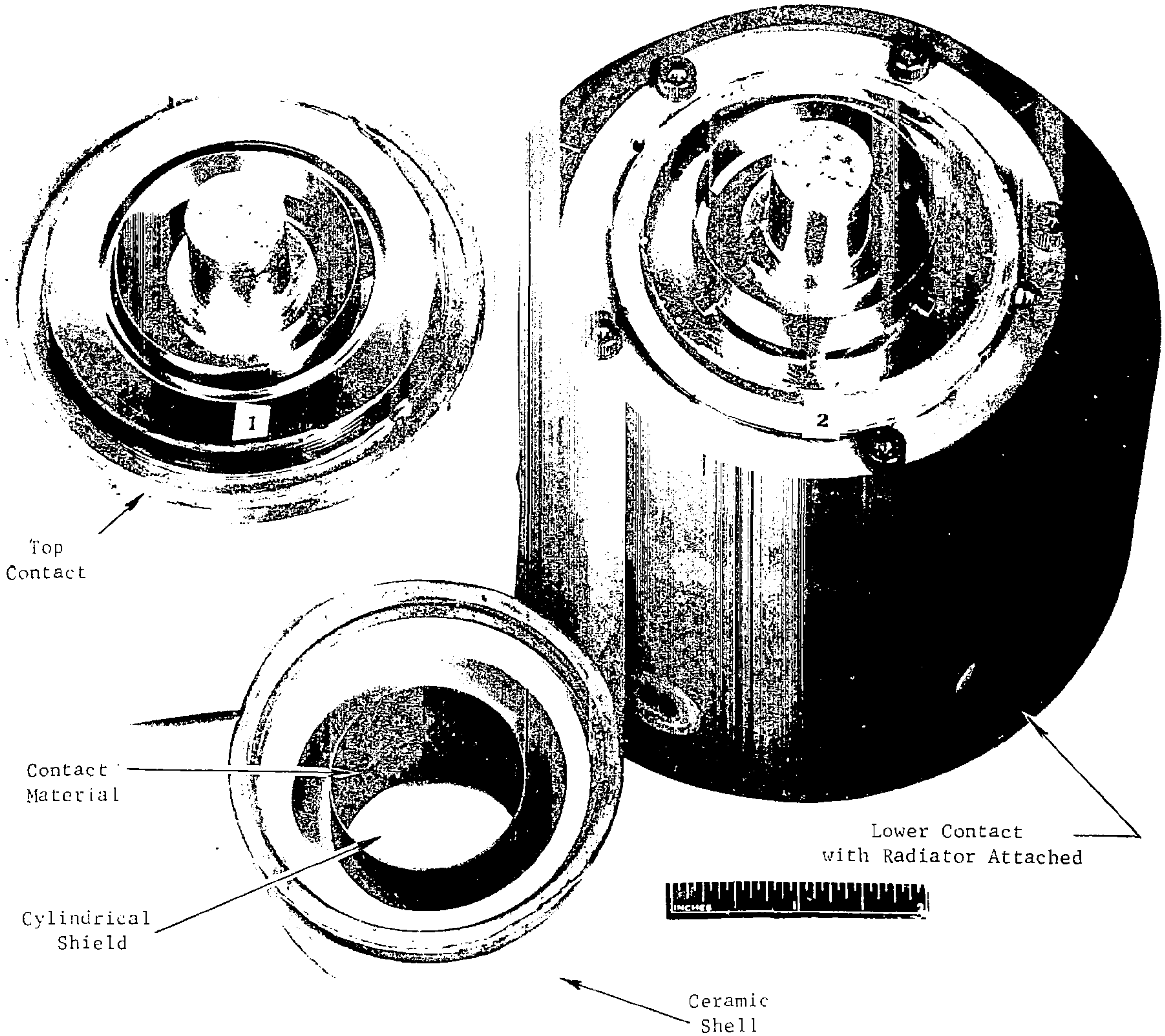
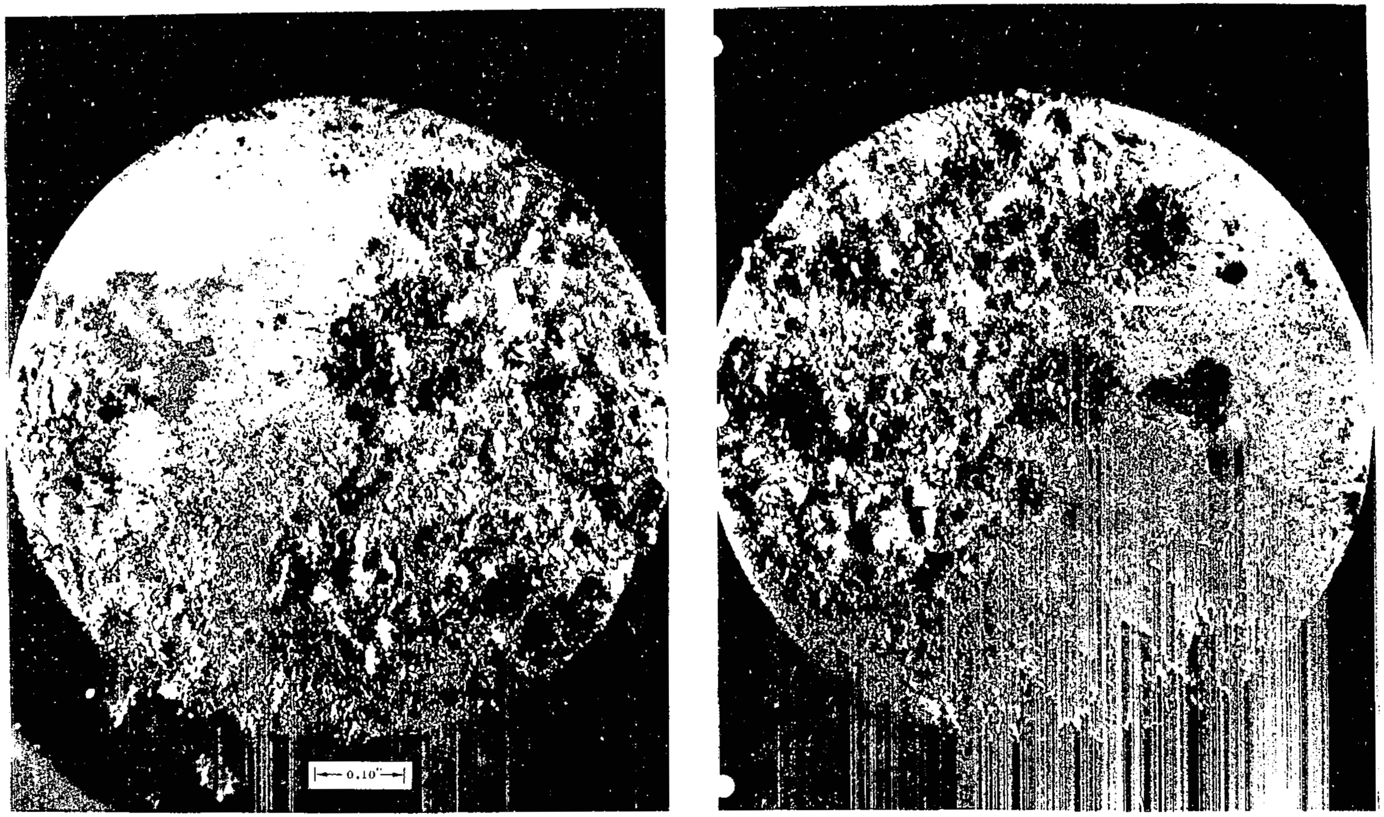


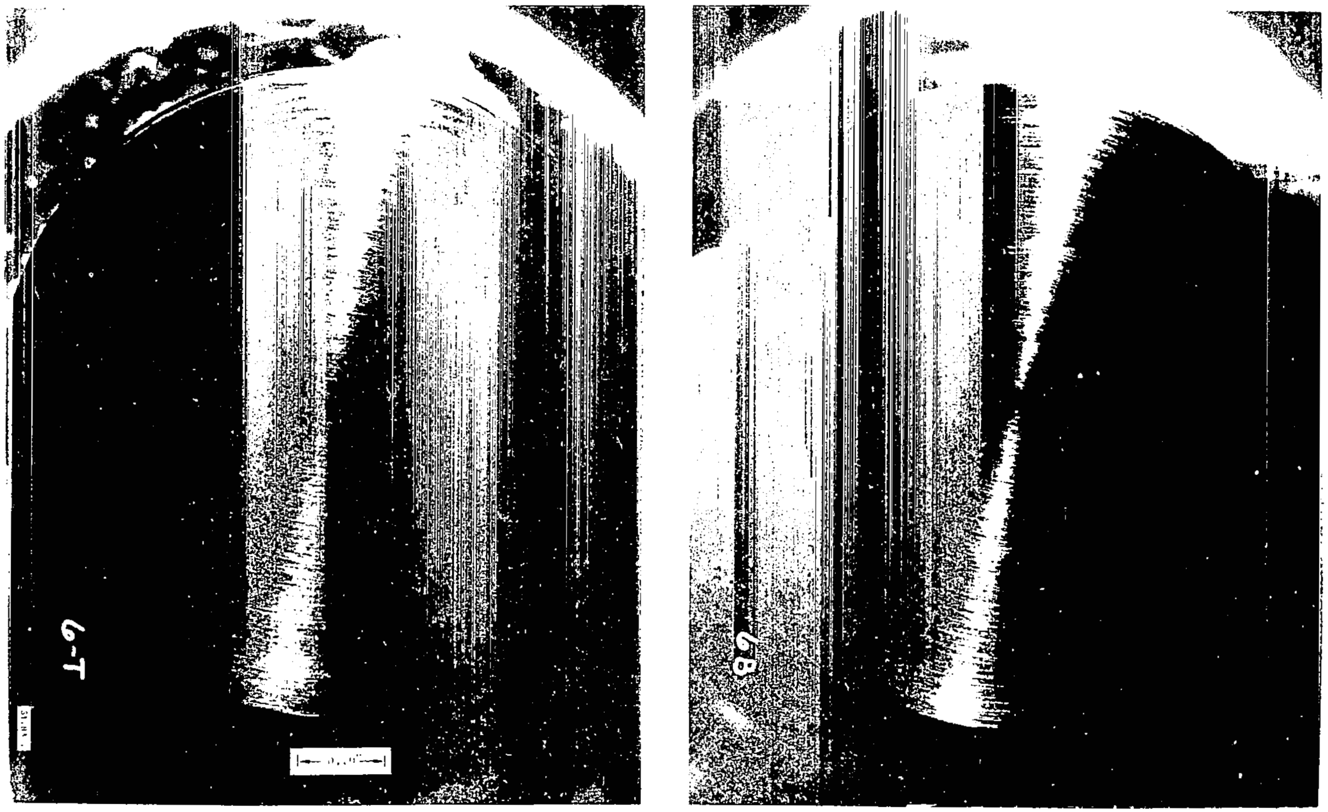
Figure 27. Breaker Contact Capsule End Flanges with the Molybdenum Contact Surfaces Showing Extensive Pitting, and the Ceramic Assembly Showing Contact Material Deposited on the Cylindrical Shield.



a. Top Contact

b. Bottom Contact

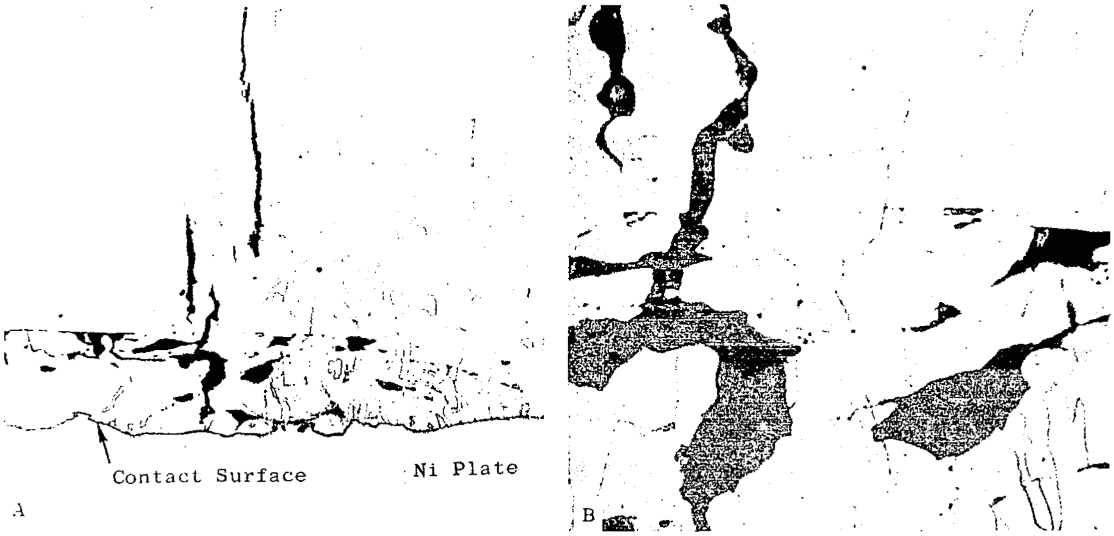
Figure 28. AC Breaker Contact Surfaces (Magnified) Showing Extensive Pitting and Erosion From Closing and Interrupting the Test Currents.



a. Top Contact

b. Bottom Contact

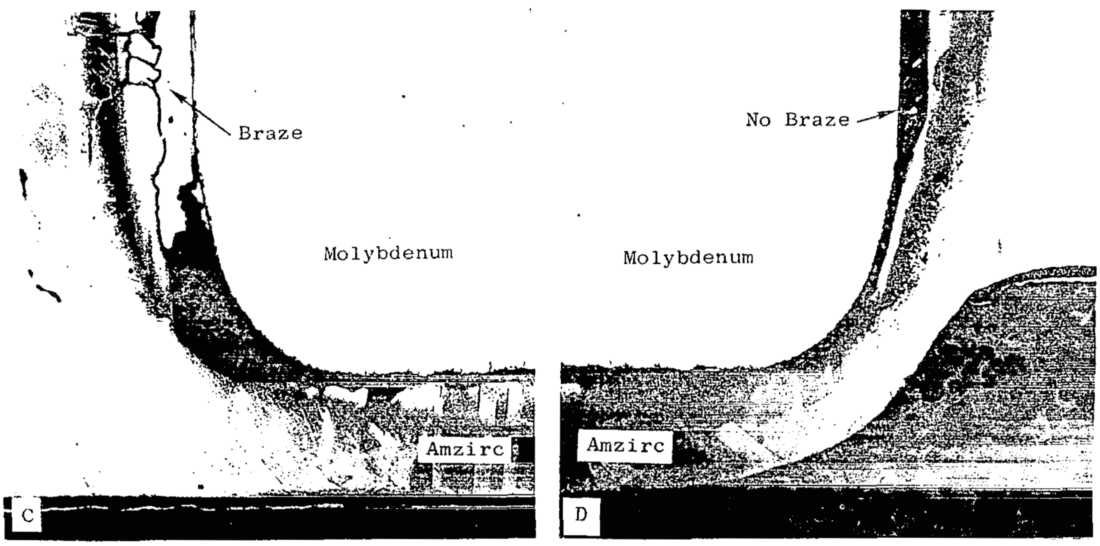
Figure 29. AC Breaker Contact Surfaces (Magnified) Before Assembly and Test.



100X - Etched with
20% Murakamis

500X - Etched with
20% Murakamis

Figure 30a and 30b. Photomicrographs of AC Breaker Contact Surface.



30X - Etched with
10 gms Fe Cl_3-30 ml HCl
and 120 ml H_2O

30X - Etched with
10 gms Fe Cl_3-30 ml HCl
and 120 ml H_2O

Figure 30c and 30d. Photomicrographs of Braze Joint Area Between Molybdenum Contact and Amzirc Flange.

APPENDIX A

MATHEMATICAL ANALYSIS OF AC SWITCHGEAR TEST CIRCUIT PERFORMANCE

The proposed AC Breaker test power supply will consist of a ringing LC circuit, and this analysis has been made to check overall circuit performance. Basic specification for values at breaker opening are:

1800 amperes rms
1000 volts rms
1000 Hz

The current response will be an exponentially decaying sinusoidal form; therefore, this analysis will determine the amount the initial values must be higher than the specified values, so that at the time of opening of the breaker, the specifications will be met. The maximum time t, for which the breaker is allowed to stay closed, before current and voltage drop below the specified levels, is calculated, and the size of the various components is determined for selected conditions.

Basic formulas used include the following:

Impedance:

$$\underline{Z} = \frac{V}{A} \qquad \text{(A1)}$$

Inductance:

$$Z = \omega L = 2\pi f L$$

$$\underline{L} = \frac{Z}{2\pi f} \qquad \text{(A2)}$$

Capacitance:

$$Z = \frac{1}{\omega C} = \frac{1}{2\pi f C}$$

$$\underline{C} = \frac{1}{2\pi f Z} \qquad \text{(A3)}$$

Resistance:

(a) of Capacitors

$$Q = \frac{1}{\omega C R} = \frac{1}{2\pi f C R}$$

$$\underline{R} = \frac{1}{2\pi f C Q} \qquad \text{where } Q = 333 \text{ @ } 1000 \text{ Hz} \qquad \text{(A4)}$$

(b) of Coil

Cable is 100 ft. long, of copper, with 1.0 sq. in. cross section.

$$R_{(DC)} = \rho \frac{\ell}{A} \tag{A5}$$

$$\underline{R} = 1.72 \times 10^{-6} \times \frac{100 \times 12 \times 2.54}{1 \times 2.54^2} = 0.81 \text{ milliohm}$$

$$\underline{R}_{(AC)} = \frac{\omega L}{Q} = \frac{0.556}{200} = 2.78 \text{ milliohm} \tag{A6}$$

(Based on assumption that Q = 200 for
DC resistance is relatively low)

$\underline{R}$ (feedthroughs + in tank) = 0.50 milliohm

$\underline{R}$ (Switchgear) = 0.60 milliohm

I. Case #1 - Proposed initial circuit values of:

v = 1200 Volts rms
A = 2160 Amp. rms
f = 1000 Hz

Determine time to reach 1000 volts rms

Impedance:

$$Z = \frac{1200}{2160} = 0.556 \text{ ohm}$$

Inductance:

$$L = \frac{Z}{2\pi f} = \frac{0.556}{6.28 \times 1000} = \underline{88.5 \text{ microhenry}}$$

Capacitance:

$$C = \frac{1}{2\pi f Z} = \frac{1}{2\pi \times 1000 \times 0.556} = \underline{287 \text{ microfarad}}$$

Resistance:

(a) Capacitors

$$R = \frac{1}{2\pi f C Q} = \frac{1}{2\pi \times 1000 \times 287 \times 10^{-6} \times 333} = 1.66 \text{ milliohm}$$

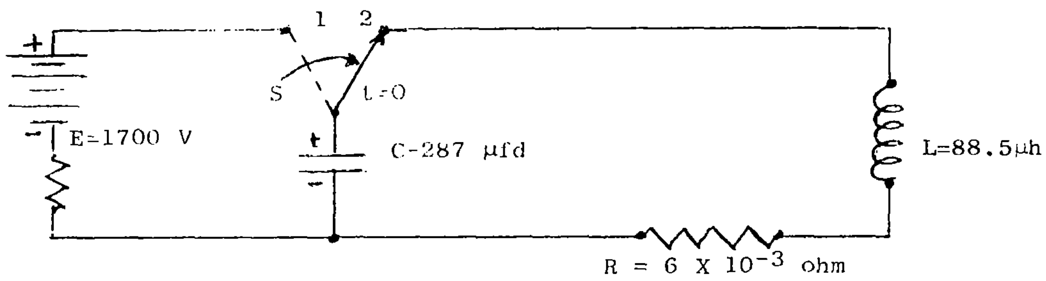
(b) Coil

$$R = \frac{\omega L}{Q} = \frac{0.556}{200} = 2.78 \text{ milliohm}$$

(c) Total Resistance

Capacitors	-	1.66 milliohm
Coil	-	2.78
Cable in Tank & Feedthrough	-	0.50
Switchgear	-	0.60
Other Lead Resistance	-	0.46
Total Resistance		6.00 milliohm

CIRCUIT PERFORMANCE CALCULATIONS:



Switch S is assumed as initially in position 1 until 1700 volts (the peak of 1200 V) appears on capacitor. Then at t=0 S is moved to position 2, and V_c (closing voltage) is impressed on the circuit.

at t=0 we have,

$$V_C\ (0^+) = L\frac{di}{dt} + Ri + \frac{1}{C} \quad i\ dt \qquad \text{(A7)}$$

differentiating equation (1) we obtain

$$0 = L\frac{d^2i}{dt^2} + R\frac{di}{dt} + \frac{i}{C}$$

$$LM^2 + RM + \frac{1}{C} = 0$$

$$M^2 + \frac{R}{L}M + \frac{1}{LC} = 0$$

$$M_{12} = \frac{-R}{2L} \pm \sqrt{\frac{R^2}{4L^2} - \frac{1}{LC}}$$

since $\frac{1}{LC} > \frac{R^2}{4L^2}$ we may rewrite the above equation in the form

$$M_{12} = a \pm jb$$

Then the general solution for equation (1) is

$$i = e^{-at} (A \sin b\,t + B \cos b\,t) \tag{A8}$$

Initial condition (1): $t = 0,\ i = 0$

$$\therefore B = 0$$

$$i = A\,e^{-at} \sin b\,t$$

Initial condition (2): $t = 0 \qquad v_c = 1700$ V

or $v_L = 1700$ V

$$v_L = L \frac{di}{dt}$$

$$v_L = L \frac{d}{dt} (A\,e^{-at} \sin b\,t)$$

$$v_L = LA\,(be^{-at} \cos bt - e^{-at} \sin bt)$$

at $t = 0, \qquad v_L = 1700$ volts

$$1700 = LAb$$

$$A = \frac{1700}{L\,b}$$

$$\text{therefore } i = \frac{1700}{Lb} e^{-at} \sin bt \tag{A9}$$

$$b = \sqrt{\frac{1}{LC} - \frac{R^2}{4L^2}} = \sqrt{\frac{1}{88.5 \times 10^{-6} \times 287 \times 10^{-6}} - \frac{(0.6 \times 10^{-3})^2}{4 \times 88.5^2 \times 10^{-12}}}$$

$$b = \sqrt{\frac{1}{LC}} = \omega$$

$$\text{then } Lb = L\sqrt{\frac{1}{LC}} = \sqrt{\frac{L}{C}} = Z$$

$$\text{and } a = \frac{R}{2L} = \frac{6 \times 10^{-3}}{2 \times 88.5 \times 10^{-6}} = 33.9 \text{ sec}^{-1} \tag{A10}$$

thus: $i = 3060\,e^{-33.9t} \sin \omega\,t$

RESULTS: - Case I

(A.) The time for the underdamped sine wave to drop to 1800 amperes rms is:

$$1800 \sqrt{2} = 3060\, e^{-33.9\, t}$$

$$\frac{1}{1.2} = e^{-33.9\, t} = 0.832$$

$$t = \frac{\ln (0.832)}{-33.9} = \frac{-0.184}{-33.9} = 5.44 \text{ ms}$$

Thus in 5.44 ms, the rms value of the current drops to 1800 amperes rms from an initial current of 3060 amperes. (2160 amperes rms). The open circuit voltage would be approx. 1000 volts, rms.

(B.) The time for the current to drop to 1200 amperes rms (from 2160 amperes, rms) is:

$$1200 \sqrt{2} = 3060\, e^{-33.9\, t}$$

$$\frac{1}{0.556} = e^{33.9\, t}$$

$$t = \frac{\ln 0.556}{-33} = \frac{0.578}{33.9} = 17.3 \text{ m sec}$$

Note: Open circuit voltage at this point would be about 667 volts, rms.

II. Case #2: For proposed initial values shown for Case #1, determine time and initial voltage to reach:

V = 1000 V rms
I = 1200 A rms
f = 1000 Hz

Impedance:

$$Z = \frac{1000}{1200} = 0.883$$

Inductance:

$$L = \frac{Z}{2\pi f} = \frac{0.883}{6.28 \times 1000} = 133 \mu h$$

Capacitance:

$$C = \frac{1}{2\pi f Z} = \frac{1}{6.28 \times 10^3 \times 8.33} = 191 \mu fd$$

Resistance:

$$R_{Cap} = \frac{1}{2\pi fCQ} = \frac{Xc}{Q} = \frac{0.833}{333} = 2.5 \text{ milliohm}$$

$$R_{Coil} = \frac{\omega L}{Q} = \frac{0.833}{200} = 4.16 \text{ milliohm}$$

Total Resistance:	Capacitor	2.50 milliohm
	Coil	4.16 milliohm
	Cable in Tank	0.50 milliohm
	Switchgear	0.60 milliohm
	Other lead etc.	0.24 milliohm
		8.00 milliohm

By (10)

$$a = \frac{R}{2L} = \frac{8 \times 10^{-3}}{2 \times 133 \times 10^{-6}} = 30 \text{ sec}^{-1}$$

$$i = A\ e^{-30t} \sin \omega t$$

Results: - Case II

The time, t, which will elapse while the current drops to 1200 amperes rms is:

$$\frac{1200}{2160} = e^{-30\ t}$$

$$558 = e^{-30\ t}$$

$$t = \frac{\ln 0.555}{-30} = \frac{0.59}{30} = \underline{19.6 \text{ ms}}$$

Note: Open circuit voltage at this elapsed time would be 1000 volts, rms.

III. Case #3: Starting with high enough initial current, determine charging current and time to open switchgear to provide:

$$V = 650 \text{ V rms}$$
$$I = 1800 \text{ A rms}$$
$$f = 1000 \text{ Hz}$$

Impedance:

$$Z = \frac{650}{1800} = 0.362$$

Inductance:

$$L = \frac{Z}{2\pi f} = \frac{0.362}{6.28 \times 1000} = 58\mu h$$

Capacitance:

$$C = \frac{1}{2\pi f Z} = \frac{1}{6.28 \times 10^3 \times 0.362} = 440\mu fd$$

Resistance:

$$R_{Cap} = \frac{1}{2\pi f C Q} = \frac{Xc}{Q} = \frac{0.362}{333} = 1.08 \text{ milliohm}$$

$$R_{Coil} = \frac{\omega L}{Q} = \frac{0.362}{200} = 1.81 \text{ milliohm}$$

Total Resistance:	Capacitor	1.08 milliohm
	Coil	1.81 milliohm
	Cable in tank	0.50 milliohm
	Switchgear	0.60 milliohm
	Other lead etc.	0.51 milliohm
		4.5 milliohm

By (10):

$$a = \frac{R}{2L} = \frac{4.5 \times 10^{-3}}{2 \times 58 \times 10^{-6}} = 38.8 \text{ sec}^{-1} \qquad t = \frac{1}{a} = \frac{1}{38.8} = 26 \text{ m sec}$$

$$i = A\, e^{-388t} \sin a\, t$$

Results:- Case III

If the starting current is 3600 amperes rms (corresponding to the charging voltage of 1840 volts) the time, t, which will elapse while the current drops to 1800 amperes rms is:

$$\frac{1800}{3600} = e^{-38.8t}$$

$$\frac{1.8}{3.6} = e^{-38.8t}$$

$$t = \frac{\ln 0.5}{-38.8} = \frac{0.692}{38.8} = 17.9 \text{ ms}$$

Note: Open circuit voltage at this elapsed time would be 650 volts, rms.

SUMMARY

The results of the study are summarized below:

Case #	L (μ H)	C (μ fd)	Initial Amps	Initial Volts	Final Amps	Final Volts	Time to Final
IA	88.5	287	2160	1200	1800	1000	5.44 ms
IB	88.5	287	2160	1200	1200	667	17.3 ms
II	133	191	2160	1800	1200	1000	19.6 ms
III	58	440	3600	1300	1800	650	17.9 ms

CONCLUSION

Case #III conditions were selected as being the most realistic for proving the breaker rating without exceeding too greatly the breaker closing capability.

NASA-Langley, 1971 —— 15